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Development and analysis of high performance hybrid cement composites

Desenvolvimento e análise de compósitos cimentícios híbridos de alto desempenho

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Abstract

In this work, the hybridization effect in cimentitious composites is studied in an attempt to modify the material and to improve the process of transference of stress of the matrix to steel fibers. Steel short fibers and steel microfibers were used in a mortar matrix for production of notched beams of 150 mm x 150 mm cross section with a length of 500 mm. Tests in beams under three point loading were conducted with crack mouth opening displacement (CMOD) control. The performance of the hybrid composites were compared with the performances of steel short fibre composites and matrix. The results were analised considering the flexional toughness and fracture tougheness parameters. The hybridization process have shown to have a satisfactory behavior translated for a strain hardening.

Keywords: *cementitious composites, hybridization, flexional tougheness, fracture toughness.*

Resumo

Neste trabalho, estudou-se o efeito da hibridização em compósitos cimentícios numa tentativa de modificar o material em sua microestrutura e melhorar o processo de transferência de tensões da matriz cimentícia para as fibras de aço. Para tanto, fibras curtas e microfibras de aço foram adicionadas a uma matriz cimentícia de argamassa para confecção de corpos-de-prova prismáticos entalhados e com dimensões de 150 mm x 150 mm x 500 mm. Os corpos-de-prova foram submetidos a ensaios de flexão com carga no meio do vão sob o controle dos deslocamentos de abertura da entrada do entalhe (CMOD). O desempenho dos compósitos híbridos foi comparado ao dos compósitos produzidos somente com a adição da fibra curta de aço e também ao da matriz sem fibras. Os resultados foram analisados considerando-se os parâmetros de tenacidade flexional e tenacidade ao fraturamento do material. O processo de hibridização permitiu obter compósitos de alto desempenho.

Palavras-chave: *compósitos cimentícios, hibridização, tenacidade flexional, tenacidade ao fraturamento.*

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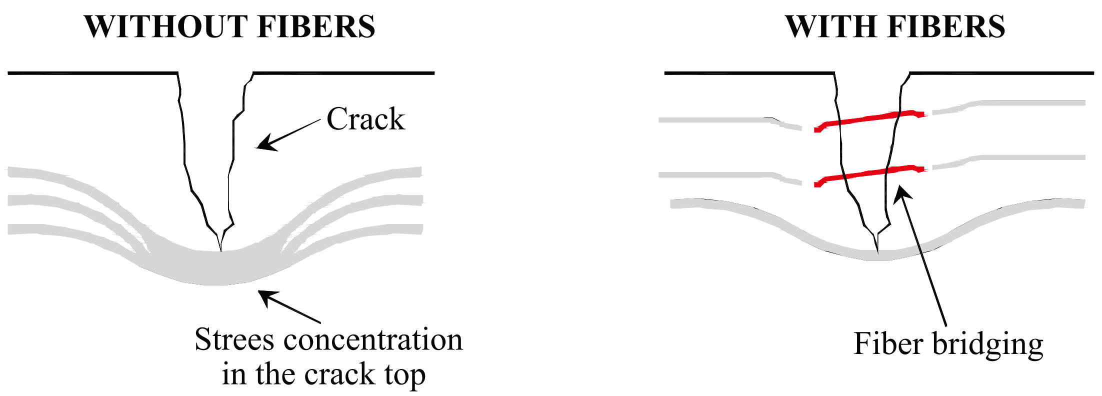
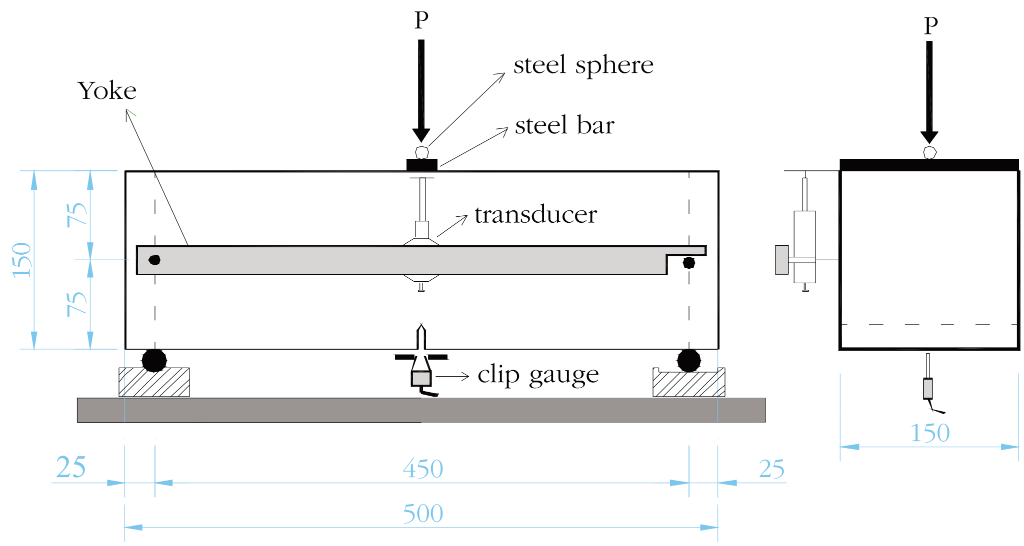
Figure 1 – Mechanism of action of steel fibers (Nunes & Agopyan (2))



1. Introduction

The cement matrix of concretes and mortars has low tensile strength comparatively to its compressive strength, a low capacity of deformation and lose almost immediately its strength after first crack.
In this regard, the addition of steel fibers with tensile strength high and ductility, improve the load capacity and deformation of the cement matrix. The presence of short steel fibers provides to the matrix a load carrying capacity postpeak and condition to support highest deformations of what the alone matrix.
According to Bentur & Mindes [1], the steel fibers are not so efficient how much the continuous reinforcement to support tensile forces, however, control the crack propagation in the concrete. They modify the mechanic behavior of the concrete after the matrix rupture and improving toughness.
The existing cracks in the concrete matrix can be intercepted by the fibers (Figure 1) who avoid the widening of the cracks due its bond with the matrix. As result, occurred a increase in the material toughness because more energy is necessary for open of the cracks. In this way, the rupture becomes less brittle on account of plastic deformations and the slipping of fibers.
The benefits of steel fibers addition to the cimentitious matrix in until 2% volume content tend to restrict only postpeak region. According to Ferreira [3], in these conditions, the steel fibers are not enough to control the matrix cracking that precede peak load (sub critical growth of the crack).
In this paper the hybridization effect is studied, that is, steel microfibers addition to conventional steel fibers in an attempt to modify

Figure 2 – Specimen dimensions (mm) and instruments disposition



composite microstructure and to improve the stress distribution between fibers and matrix.

2. Experimental program

2.1 Test methods

Flexural tests in prismatic specimens were carried according to the requirements of RILEM [4] to evaluate the flexural tensile behavior of cimentitious composites of high performance.
The specimens with initial notch depth 25 mm and width 2 mm were tested. The objective of the notch is to induce the fracture in a preferential plane and increase the stress to the notch top. Thus, during the specimen test, the deformation always occurs in the notch plane and the volumetric energy dissipation is reduced.
In the figures 2 and 3 is possible to observe the tests carried in the LE – Laboratory of Structures of the Engineering School of São Carlos. For measurement of the load-line deflection a transducer was used. This equipment was fixed in a support called Yoke. Servohydraulic Instron equipment was used with a load-cell of 100 kN. The tests were carried at notch mouth opening displacements control (CMOD) using a clip gauge. The tests operation was carried out at a clip gauge opening rate of 0.02mm/min for CMOD until 0.1mm. After this value, the rate was increased for 0.04mm/min.

2.2 Test programs

Were molded twenty and four prismatic specimens with 150 mm x 150 mm x 500 mm. The specimens were divided in eight groups. A set of eight different composites was formed, from the variation of the volume and the type of the steel fiber. Each composite received the following identification:

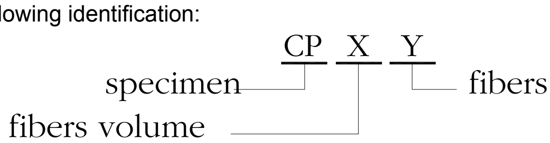


Figure 3 – Specimen detail for testing scheme

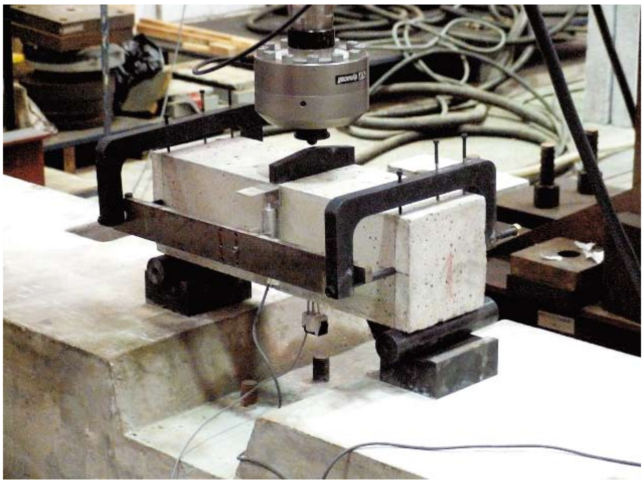


Table 1 – Composites, fibers and microfibers

Group		Composites	Fiber volume	Fiber type	Material	Age
1		CP	0%	-	mortar	29 dias
2	Individual fiber	CP1A	1%	A	mortar	29 dias
3	Individual fiber	CP1.5A	15%	A	mortar	29 dias
4	Individual fiber	CP2A	2%	A	mortar	29 dias
5	Hybrid	CP1.5A0.5C	1.5%+0,5%	A+C	mortar	28 dias
6	Hybrid	CP1.5A1.5C	1.5%+1.5%	A+C	mortar	28 dias
7	Hybrid	CP1.5A2.5C	1,5%+2.5%	A+C	mortar	28 dias
8	Hybrid	CP1.5A3.5C	1.5%+3.5%	A+C	mortar	28 dias

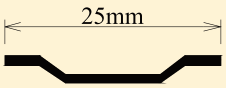
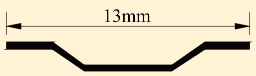
Fibers parameters	Fiber A: FS-8 Wirand	Fiber C
Longitudinal aspect		
Nominal diameter	0.75 mm	0.75 mm
Aspect ratio	33	17
Maximum tensile stress	1100 MPa	1100 MPa

Table 2 – Average results of composites characterization

Groups		Composites	f_{cm} (MPa)	$f_{ctm,sp}$ (MPa)	E_{cs} (MPa)
1		CP	52.54	3.07	23839
2	Individual fiber	CP1A	43.78	3.68	22696
3	Individual fiber	CP1.5A	42.24	3.70	23100
4	Individual fiber	CP2A	45.68	4.92	23974
5	Hybrid	CP1.5A0.5C	49.23	4.44	28217
6	Hybrid	CP1.5A1.5C	47.22	4.89	32261
7	Hybrid	CP1.5A2.5C	43.55	4.75	31041
8	Hybrid	CP1.5A3.5C	42.76	4.88	29137

Observations: For each composite were tested 3 specimens to axial compression and 3 to tensile for diametral compression using cylindrical specimens with diameter of 100 mm and height of 200 mm.
Ecs – is the deformation secant modulus correspondent to secant straight line to stress-strain diagram who intercept the points with 0.5MPa stress and to 30% stress of rupture.

The composites were molded using a cimentitious matrix with strength compressive of 50 MPa. The mortar was used in an attempt to develop a composite for applications in structural repairs (for example, the damaged bottom of reinforced concrete beams). In the Table 1, the composites, fibers and microfibers are presented. The fiber "A", have a commercial name FS-8 Wirand and were supplied for the company Maccaferri – Latin America, length of 25 mm, with hook and diameter of 0.75 mm.
The objective of this paper is to study the effect of the addition of steel microfibers to FS-8 fibers. A steel microfiber with length of 13 mm and diameter of 0,75 mm was used. These microfibers, supplied for the company Maccaferri, were identified for "C".
The hybrids composites were molded fixing the steel short fibers volume in 1,5% and changing the steel microfibers volume. This volume of short fiber was defined by being an intermediate value between 1% and 2% of fibers and also, biggest capacity of energy absorption observed in curve P-CMOD (item 3.2.2) of CP1.5A composite (1.5% of fibers) in relation to CP1A (1% of fiber) and of similar performance P-CMOD curve CP2A composite.

2.3 Composites dosage

The composites were mixed according to 1:3 proportions of cement and aggregate. Cement consumption was 500 kg/m^3 and the relation a/c was 0.5. The workability of fresh mortar was controlled by adding of superplasticizer. Portland cement of initial strength high was additioned to give high profits of strength already in the first ages.
To proceed to the mixture of the materials, an electric mixer with capacity of 50 L was used. The used procedures in the mixture had been: a) mixture of the sand and cement for about 1 minute; b) random addition of steel fibers and microfibers during the mixture still dry; c) addition of water and additive to the mixture. The time of each mixture was of approximately six minutes, being after carried until the place from the casting.
Six cylindrical specimens diameter of 100 mm and height of 200 mm were molded for each composite with the objective to get the compressive strength, the tensile strength and the modulus of elasticity. The cylindrical specimens were keep in the same conditions of homogenize and curing – storage in humid room until the test date. The Figure 4 shows a detail of the materials mixture.

3. Results and discussion

3.1 Compression tests in cylindricals specimens

The mechanical properties of composites: compression strength (f_{cm}), tensile strength ($f_{ctm,sp}$) and the modulus of elasticity (E_{cs}) are listed in Table 2. These properties were obtained in the same age of the flexural tests when the composite age was 28 or 29 days old.
It was found that with steel fibers addition the axial compressive strength decreased. The ACI 544.2R [5] comments that the steel fibers, in volume normally used (until about 2%) does not add substantial improvements in the compressive strength of the concrete, being able until leading to a small reduction in this property.
In relation to the matrix, the composite CP1.5A presented the biggest reduction, about 24%, while the CP1.5A0.5C showed only 7% of difference. It was observed that steel fibers have significant influence in the reduction of the compressive strength of the mortar cimentitious composites. This fact can be related to the paper that the steel fibers exert in the air capture for the matrix.
With regard to the values of tensile strength, it was found that the composites with fibers demonstrated highest strengths than matrix without fibers. The highest increase was 60% (composite CP2A) and the lowest was 20% (composite CP1A). Comparing the strength of 3.70 MPa (composite CP1.5A) with the 4.44 MPa (composite CP1.5A0.5C), showed that presence of steel microfibers improved this property.

The modulus of elasticity of composites with individual fiber is equal to the matrix without fibers. For the hybrid composites, the modulus of elasticity is always higher than the matrix without fibers. Increased of the 18% (CP1.5A0.5C) and 35% (CP1.5A1.5C) were observed.

3.2 Flexural tests in prismatic specimens

3.2.1 Loads and strengths according to RILEM

The toughness flexional of the cimentitious composites were obtained following the recommendations prescribed for the work group TC 162-TDF of the RILEM. This group has been distinguished in the scope of the tests normalization for characterization of cimentitious materials with fibers and for the establishment of parameters for analysis of steel fibre-reinforced structures concrete.
The toughness evaluation method for the RILEM [4] is based on the capacity absorption energy in terms of area under the load-deflection curve P-δ (P is the load and δ is vertical displacement). The fibers contribution for the toughness of the composite is evaluated through the subtraction of the toughness parcel that comes of the matrix.
The typical behavior of the composites to the flexural is showed in the Figure 5. The equivalent flexural tensile strength ($f_{eq,2}$ e $f_{eq,3}$) and residual flexural strengths ($f_{R,1}$ e $f_{R,4}$) are determined by means expressions indicated in the Figure 5.
F_L – is equal to the highest value of the load in the interval δ of 0.05mm. This interval is gotten with the aid of a parallel straight line to the initial tangent, passing for the point that characterizes the offset displacement. This geometric procedure is part of the recommendations of previous versions of the RILEM. The current version allows take F_L as being the biggest value of load in the interval of δ=0,05mm. Here, with aid of a computational tool called TENAC (Ferreira [6]), it was possible to consider the value of F_L as being of offset.
δ_L – is the displacement vertical of F_L;

$f_{fct.L}$ – is the stress of F_L, calculate using the expression: $f_{fct.L} = \frac{3.F_L.L}{2.b.h_{sp}^2}$;

L – span of the specimen and b width;
h_{sp} – distance between tipo f the notch and top of cross section;
D^b_{BZ}, $D^f_{BZ.2}$ e $D^f_{BZ.3}$ – energy absorption capacity for the matrix and fibers, respectively, is equal to the área under load-deflection curve up to a specifics deflections (see Figure 5);
$F_{R.1}$ e $F_{R.4}$ – loads values correspondents at δ_{R1}=0.46 mm e δ_{R4}=3.00 mm.
In accordance with the RILEM [4], the terms ($D^f_{BZ,2}$ e $D^f_{BZ,3}$) is transformed into equivalent flexural strengths ($f_{eq,2}$ e $f_{eq,3}$). The material load capacity in relation deflection defined is evaluate between of the residual flexural strengths concepts ($f_{R,1}$ e $f_{R,4}$). The loads and strengths calculated according to RILEM [4] are showed in Table 3.
The F_M load is presented in the Table 3. This load correspondent to the maximum load. Following a European trend, the RILEM discarded the concept of first-crack strength and started to adopt the offset maximum load.
The $f_{fct,L}$ value, according to RILEM [4], corresponds to the force F_L. The $f_{fct,L}$ represents the strength proceeding from the contribution of the cimentitious matrix. The equivalents flexional strengths values ($f_{eq,2}$ e $f_{eq,3}$) represent the composite behavior proceeding from the steel contribution in the material strength. Thus, the matrix strength was increased with the steel fibers addition.
In the hybrid composites were observed trend of increase of $f_{ct,L}$. This increased occurred in function of addition microfibers until 2.5%. The composite CP1.5A0.5C showed bigger strength than CP1.5A (without steel microfibers) and smaller than the others: CP1.5A1.5C and CPA1.5A2.5C. The elevate fibers volume in the CP1.5A3.5C can have prejudiced the matrix performance.
The strengths values ($f_{eq,2}$ e $f_{eq,3}$) characterize the composites behavior in relation to the fibers performance. The performance composites are evidenced CP1.5A, CP2A, CP1.5A0.5C, CP1.5A1.5C, CP1.5A2.5C e CP1.5A3.5C. In this composites the steel fibers increased the material strength and the equivalent flexional strength ($f_{eq,2}$) elevated the strength value given only for matrix contribution ($f_{fct,L}$).
In the Figure 6 the relation between maximum load of offset (F_L) and the maximum load supported by composites (F_M) is analyzed. In this composites represented for a only color, the load F_M is equal the F_L, that is, the fibers had not provided increase of load capacity

Figure 5 – Evaluation of the behavior of materials with fibers according to RILEM

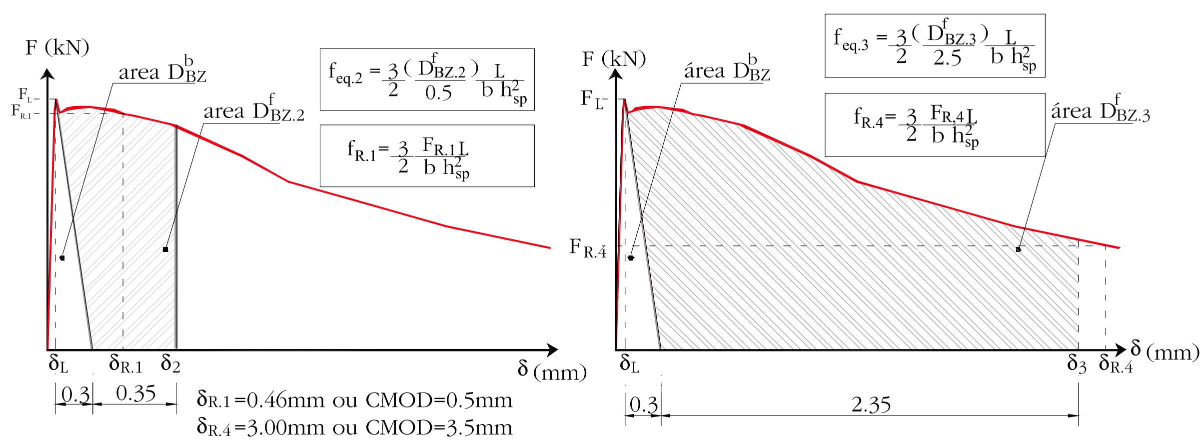


Table 3 – Loads and strengths according to RILEM (4)

Composites	Loads				Strengths				
	F_L (kN)	F_M (kN)	$F_{R,1}$ (kN)	$F_{R,4}$ (kN)	$f_{fct,L}$ (MPa)	$f_{eq,2}$ (MPa)	$f_{eq,3}$ (MPa)	$f_{R,1}$ (MPa)	$f_{R,4}$ (MPa)
CP	8.00	8.00	1.26	-	2.33	-	-	0.37	-
CP1A	13.41	13.41	12.46	5.22	3.87	3.31	2.58	3.60	1.51
CP1.5A	13.15	16.10	16.01	6.10	3.73	4.58	3.16	4.54	1.73
CP2A	14.50	17.59	17.35	7.59	4.56	5.53	4.20	5.45	2.38
CP1.5A0.5C	16.41	17.78	17.23	9.32	4.58	4.94	3.98	4.79	2.61
CP1.5A1.5C	16.01	20.95	20.91	9.42	4.79	6.46	4.80	6.25	2.81
CP1.5A2.5C	17.43	19.30	17.87	4.20	5.18	5.42	3.40	5.15	1.21
CP1.5A3.5C	14.31	15.55	15.18	8.12	4.18	4.47	3.60	4.37	2.34

beyond the contribution of the matrix. In the composites where two colors appear, the load F_M is bigger than F_L, that is, the load capacity is increased by the fibers contribution.
It is evident that the addition of 1% steel fibers was not enough to raise the load capacity of CP1A composite beyond the contribution given for the cimentitious matrix. Already in the other composites, in special in the hybrids, its load capacity was increased beyond the contribution given for the matrix.
In the hybrid composites the matrix load capacity was higher than composites with single fiber. This is reflecting of the steel microfibers action in the initial stage of material solicitation.

3.2.2 P-CMOD curves

The P-CMOD curves are presented in the appendix of the reference [3]. The behavior of the each composite is represented for the average curve. P-CMOD curves of cimentitious composites are presented in the Figure 7.
The steel fibers and microfibers in the matrix improved its behavior. Increase in the energy capacity absorption and raise of the resistance before and after matrix rupture were observed. The increase in the A fibers volume provided improvement in the ductility of these composites. The incorporation of the C microfibers contributed still more in this aspect.
The energy absorption capacity of the composite CP1.5A was increased in the same level of the composite CP2A with the addition of 0.5% microfibers. Still better answers had been gotten with the increase in the microfibers volume until 1.5%. The composites development with 2.5% and 3.5% of microfibers was not better than CP1.5A1.5C.

Figure 6 – Offset maximum load (F_L) and composite maximum load (F_M)

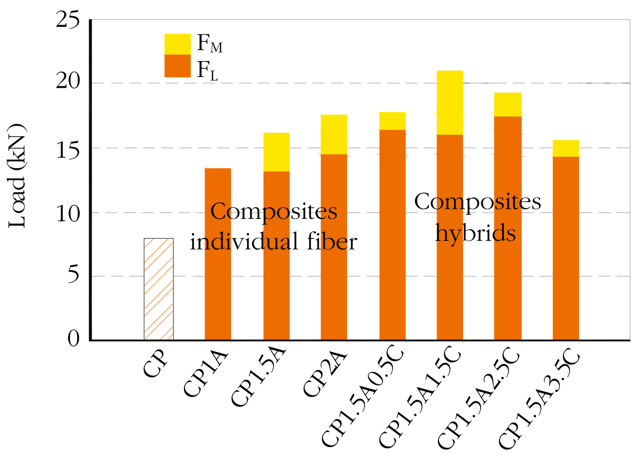


Figure 7 – P-CMOD curves

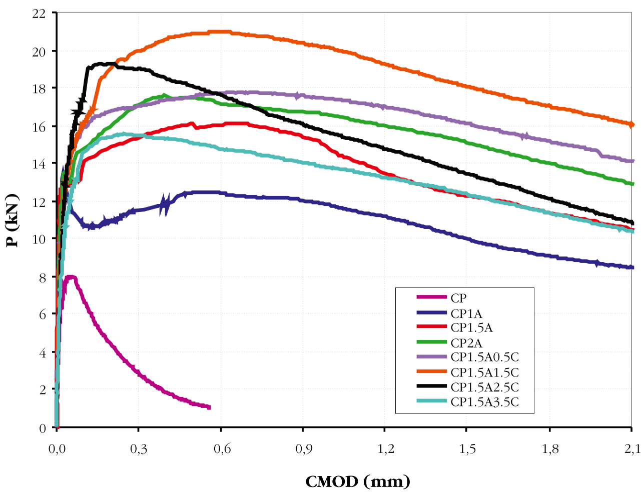
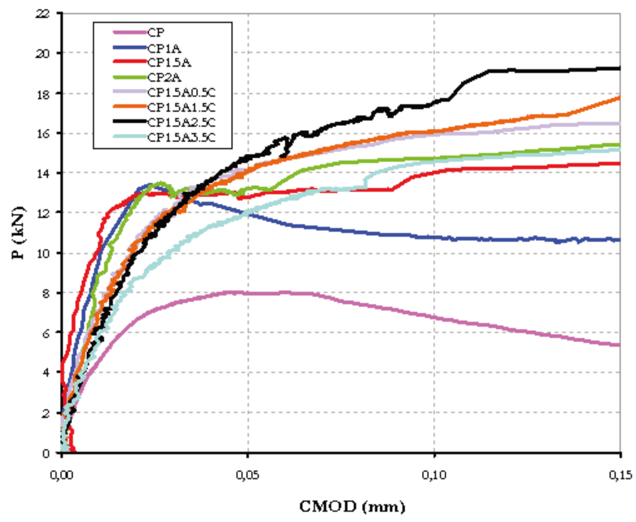


Figure 8 – P-CMOD curves – initial solicitation interval of the composites



The curves showed in the Figure 7 are presented in the Figure 8. The composites solicitation initial interval (CMOD until 0.15mm) is emphasis in this figure. The microfibers effects in the material are better to understand between the Figure 8.

The composites initial stiffness was decreased with the presence of microfibers. The interval after the matrix cracking in the composites with single fiber A is clearly defined (constant resistance and changeable CMOD). The stress transference when has microfibers in the matrix occurred with increase in the composites load capacity.

The stress transference during the matrix cracking is facilitated for the great amount of microfibers in the matrix. The microfibers in the matrix increase the possibility of the crack be intercepted by a fiber. In this way, the growth of the crack is conditional to the rise of the loading applied to the composite.

3.2.3 Fracture resistance curves

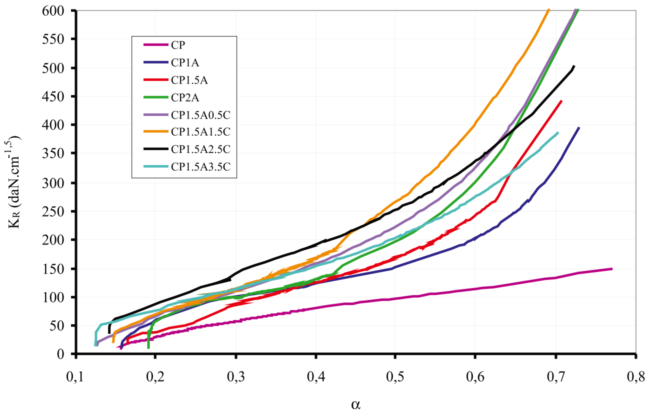
The P-CMOD curves experimentally obtained are analyzed under the approach of Fracture Mechanic. Fracture resistance curves had been plotted following the methodology suggest by Ferreira [3].

The resistance curves of the cimentitious composites are presented in the Figure 9. In this figure K_R is the fracture resistance and α is the crack depth (a) normalized relatively to the height (W) of the prismatic specimen, that is α = a/W.

Some considerations about the cimentitious composites performance to the crack propagation is possible to write from the resistance curves analysis. The steel fibers addition to the mortar matrix increased the resistance to the crack growth in relation to the matrix without fibers (CP).

The growth of resistance fracture was evidenced after postpeak rupture regimen increasing with the increase of fibers in the composites with individual fibers. The growth of resistance fracture in the hybrids composites gradually increased with the increase of microfibers until the 2.5% volume. A best performance from this volume was not observed.

Figure 9 – Resistance curves of cimentitious composites



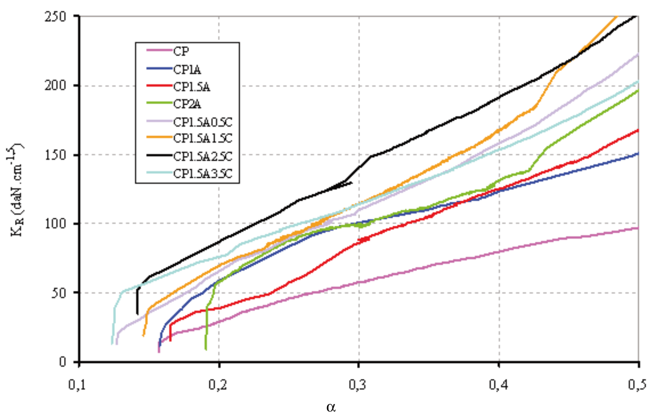
The final intervals of hybrids composites resistance curves CP1.5A0.5C and CP1.5A1.5C are more ascending than the others. This fact represents the increase crack propagation resistance proportionate for presence of steel fibers and microfibers and is related to the energy dissipation in the fibers pull out process.

In the Figure 10 the resistance curves are showed with the limits α = 0.5 e K_R = 250 daN.cm$^{-1,5}$.

For the matrix without fibers is observed a resistance capacity small to the crack propagation. This fact evidence the cracks subcritical growth eventually for the absence of coarse aggregate in the mixe. On the other hand, the presence of steel fibers and microfibers in the mixe delayed this phenomenon.

The fracture resistances of hybrids composites were bigger than to the composites with individual fiber for initial propagation of crack (α = 0,2). This fact is related to the steel microfibers presence. The microfibers tie the crack propagation with the solicitation applied in

Figure 10 – Resistance curves – α < 0,5



the composite. However the results show to exist a volume of steel microfibers from which is not possible to get better performance for the composite.
How show in the Figure 9, the growth of resistance fracture of composites occurred according to two well defined stages. The cracking initial stage – characterized for an increase slight in the fracture toughness – and the end stage of crack process – where the fracture resistance increased significantly.
In the end stage is where start the tensile process of steel fibers and microfibers and the stress transference between faces of the crack by means of these fibers. This stage characterizes by bigger than evolution of fibers in relation the fracture resistance growth.
In the end stage of cracking process is observed the considerable increase of fracture resistance of composite. This fact occurs on account of the pulling up of the fibers anchored to the matrix. In this stage the efficiency of fibers in relation to the increased of fracture toughness is remarkably reflected.

4. Conclusions

Based on analysis and discussion presented in this paper, the following can be concluded:

- The use of steel fibers and microfibers is an interesting alternative for application in the field of structural rehabilitation. The fibers addition in the cimentitious matrix have conditions to increase the flexural tensile strength and fracture toughness of the material;
- The hybridization process, that is, the addition of steel micro fibers beyond conventional fibers provide a bigger contribution of the matriz for the composite resistance and improves the mechanism of stress transference of the matrix for fibers;
- With the matrix cracking, the stress transference was improved for steel microfibers. The microfibers in elevate number in the matrix tied the cracks propagation to the loading increase;
- The hybrid composite CP1.5A1.5C showed to be adjusted for applications in members tensile of reinforced concrete. This fact is evidenced by continuous increase of fracture resistance and the pseudo-hardening characteristic (increase in the composite load capacity after cracking);
- The behavior obtained with the hybrid composite CP1.5A2.5C must be commented. This composite showed fracture resistance in the initials stages of loading slightly greater than the composite CP1.5A1.5C. However the composite CP1.5A2.5C showed flexural toughness and tensile strength of the composite lower than CP1.5A1.5C.

5. Acknowledgements

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