ALCONPAT Journal, Volume 6, Issue 1, january - april 2016, Pages 52 – 63

ALCONPAT Journal

http://www.revistaalconpat.org

eISSN 2007-6835

Journal of the Latin-American Association of Quality Control, Pathology and Recovery of Construction

High performance cementitious compounds and their application as transition substrate for beams

V. J. Ferrari[1], A. P. Arquez[2], J. B. De Hanai[2]

[1] Department of Civil Engineering, Universidade Estadual de Maringá, Brazil.
[2] Escola de Engenharia de Sao Carlos, Universidade de Sao Paulo, Brazil.

Article information
DOI:
http://dx.doi.org/10.21041/ra.v6i1.115
Article received on november 30th 2015, reviewed under publishing policies of ALCONPAT journal and accepted on january 20th 2016. Any discussion, including authors reply, will be published on the third number of 2016 if received before closing the second number of 2016.

Legal Information
ALCONPAT Journal, year 6, No. 1, January-April 2016, is a quarterly publication of the Latinamerican Association of quality control, pathology and recovery of construction-International, A.C.; Km. 6, Antigua carretera a Progreso, Mérida, Yucatán, C.P. 97310, Tel.5219997385893, alconpat.int@gmail.com, Website: Revista ALCONPAT.
Editor: Dr. Pedro Castro Borges. Reservation of rights to exclusive use No.04-2013-011717330300-203, eISSN 2007-6835, both awarded by the National Institute of Copyright. Responsible for the latest update on this number, ALCONPAT Informatics Unit, Eng. Elizabeth Maldonado Sabido, Km. 6, Antigua carretera a Progreso, Mérida Yucatán, C.P. 97310, last updated: March 30th, 2016.

ABSTRACT

This study presents the development and analysis of the behavior of high performance cementitious compounds reinforced with fibers. The material described was specifically developed for its application as a transition substrate, meaning, a repair layer that forms the tensed span of the flexion reinforced concrete beams with carbon fiber reinforced polymers (CFRP). Nineteen different compounds were produced by the hybridization process. The volume of the short fibers and of the steel microfibers varied. To analyze the behavior of the flexural material, tests were done in three points in tests tubes with their notches. The response of the material was analyzed considering the tenacity parameters (to flexion and fracture). The high performance of the compounds through the behavior of pseudo-hardening was confirmed.

Keywords: cementitious compounds; concrete beams; transition substrate.

RESUMEN

Este estudio muestra el desarrollo y análisis del comportamiento de los materiales compuestos de cemento reforzado con fibras de alto rendimiento. El material descrito se desarrolló específicamente para su aplicación como sustrato de transición, o capa de reparación de la formación de la brida tensada vigas de hormigón reforzado con polímeros de flexión reforzado con fibras de carbono (PRFC). Diecinueve compuestos diferentes fueron producidos por el proceso de hibridación. Se varió la cantidad de fibras cortas y microfibras de acero. Para analizar el comportamiento de los ensayos de flexión en tres puntos materiales prismas se realizaron Jagged. La respuesta del material se analizó teniendo en cuenta parámetros de tenacidad a la flexión y (fractura). Materiales compuestos de alto rendimiento evidencia a través de un comportamiento pseudo- endurecimiento.

Palabras clave: compuestos cementíceos; vigas de concreto; sustrato de transición.

RESUMO

Neste estudo apresenta-se o desenvolvimento e a análise do comportamiento de compuestos cementíceos de elevado desempeño reforzados com fibras. O material descrito foi especificamente desarrollado para aplicación como um sustrato de transición, ou seja, camada de reparo que forma o banzo traccionado de vigas de concreto reforçadas à flexão com polímeros reforzados com fibras de carbono (PRFC). Dezenove diferentes compuestos foram produzidos pelo processo de hibridização. Variou-se o volume de fibras curtas e de microfibras de aço. Para analisar o comportamiento do material à flexão, ensaios em três pontos em prismas entalhados foram realizados. A resposta do material foi analisada considerando-se parâmetros de tenacidade (flexional e ao fraturamento). Ficou evidenciado o elevado desempeño dos compuestos através de comportamiento de pseudo-encruamento.

Palavras-chave: compuestos cementíceos; vigas de concreto; sustrato de transición.

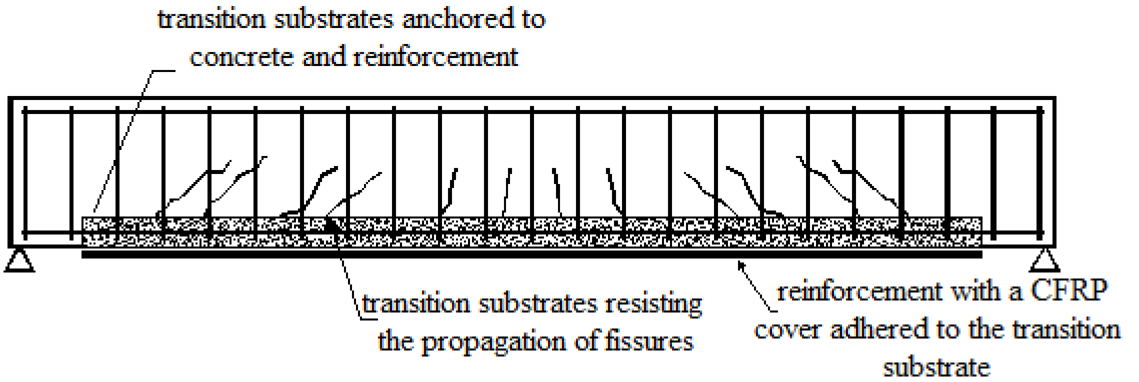
Contact author: Vladimir Ferrarí (vladimirjf@hotmail.com)

1. INTRODUCTION

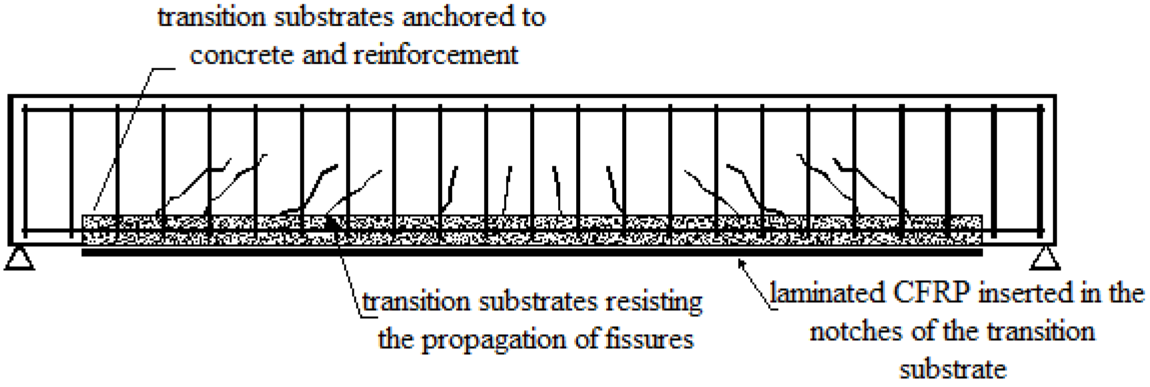
According to Ferreira (2012), the resulting modifications of the addition of steel fiber to concrete, in relatively low proportions (a maximum of 2%), are restricted to the later stage at the historical load peak. In these conditions, the steel fibers are not enough to inhibit the cracking process of the matrix, which occurs before the application of the maximum load (sub-critical growth of the crack). The effect of the incorporation of steel microfibers, the short fibers studied here are an attempt to improve the behavior of the cementitious compounds in the historical load pre-peak.

Those materials were specifically developed to be applied as transition substrates (Figure 1). Nineteen different compounds were prepared in two phases: Phase I (compounds that were developed for their application as transition substrates for reinforced concrete beams for the external placement of CFRP covers- Figure 1.a) and Phase II (compounds developed for their application as transition substrates of reinforced beams through the insertion of CFRP sheets in the notches made in this substrate – Figure 1.b).

In engineering, it is common to find reinforced concrete beams with a tensioned underside damaged by mechanical action, corrosion effects on the reinforcement, or cracking. In such cases, the beam reinforcement process should be preceded by the recovery of the side. For this, Ferrari (2012) proposes a cement based, high performance compound cement intended to be part of the transition substrate such as the one indicated in Figure 1. The concept of the transition substrate is to create a new tensioned side formed by the cementitious compound with more appropriate characteristics to the adherence of the polymeric reinforcement.



a) External reinforcement with a CFRP cover adhered to the transition substrate (Ferrari, 2012)



Laminated CFRP inserted in the notches of the transition substrate (Arquez, 2010)

Figure 1. Transition substrate with CFRP for reinforced concrete beam.

In this study, new results were added to the ones presented by Ferrari (2012). The new results were obtained through the development and analysis of cementitious compounds to form the transition substrate of reinforced beams through the insertion of CFRP sheets in the notch of the new substrate.

2. HIGH PERFORMANCE CEMENTITIOUS COMPOUNDS

To evaluate the resistance to traction in the flexion of the cementitious compounds, tests were carried out on three points of the prismatic test tubes (150mm x 150mm x 500mm) equipped with a central notch with a direct pass and following the Rilem (2002) recommendations. Figure 2 shows the general configuration of the test that was conducted by controlling the crack mouth opening displacement (CMOD).

In phase I, thirteen compounds were analyzed as shown in Table 1. The compounds were comprised of different volumes and types of steel fibers and by different types of cementitious matrices (mortar and micro-concrete). The compounds were divided into groups, each one comprised of three prismatic test tubes with the same characteristics. In phase II, an additional group comprised of six compounds (all made of micro-concrete) was studied.

The steel fiber specified by “A” is 25 mm long and has a diameter of 0.75 mm. The type “C”, fiber, specifically produced for this investigation, is 13 mm long and has a diameter of 0.75 mm. This fiber has been designated as a steel microfiber (Figure 3).

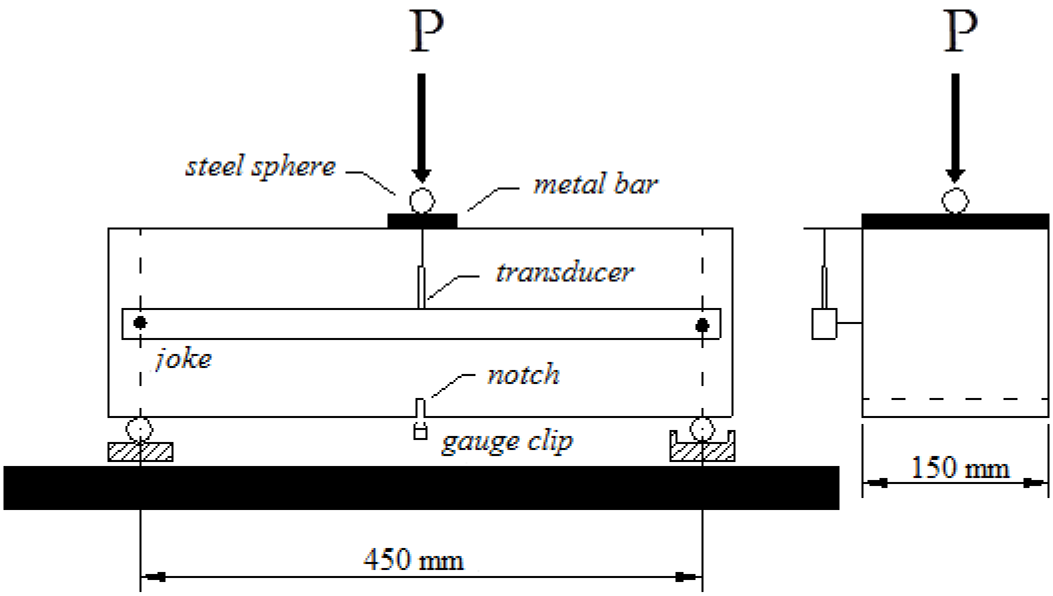
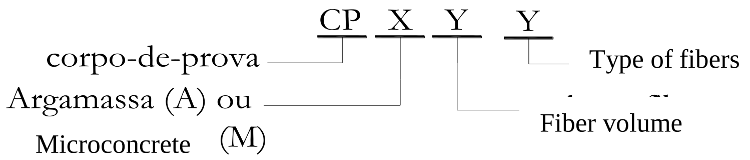


Figure 2. General configuration of the test

Table 1. Compounds analyzed

Matrix	Phase	Group	Compounds	Fiber volume	Type of fibers	Material	Age (days)
Mortar (A)	**I**	1	CPA	0%	-	Mortar	29
		2	CPA1A	1%	A	Mortar	29
		3	CPA1.5A	1.5%	A	Mortar	29
		4	CPA2A	2%	A	Mortar	29
		5	CPA1.5A0.5C	1.5%+0,5%	A+C	Mortar	28
		6	CPA1.5A1.5C	1.5%+1.5%	A+C	Mortar	28
		7	CPA1.5A2.5C	1,5%+2.5%	A+C	Mortar	28
		8	CPA1.5A3.5C	1.5%+3.5%	A+C	Mortar	28
Micro-concrete (M)	**I**	9	CPM	0%	-	microconcre	28
		10	CPM1A	1%	A	microconcre	28
		11	CPM1A1C	1%+1%	A+C	microconcre	28
		12	CPM1A2C	1%+2%	A+C	microconcre	28
		13	CPM1A2.5C	1%+2.5%	A+C	microconcre	28
Micro-concrete (M)	**II**	1	CPM1A1C	1%+1%	A+C	microconcre	50
		2	CPM1A1.5C	1%+1.5%	A+C	microconcre	50
		3	CPM1A2C	1%+2%	A+C	microconcre	50
		4	CPM1.5A1C	1,5%+1%	A+C	microconcre	50
		5	CPM1.5A1.5C	1.5%+1.5%	A+C	microconcre	50
		6	CPM1.5A2C	1.5%+2%	A+C	microconcre	50



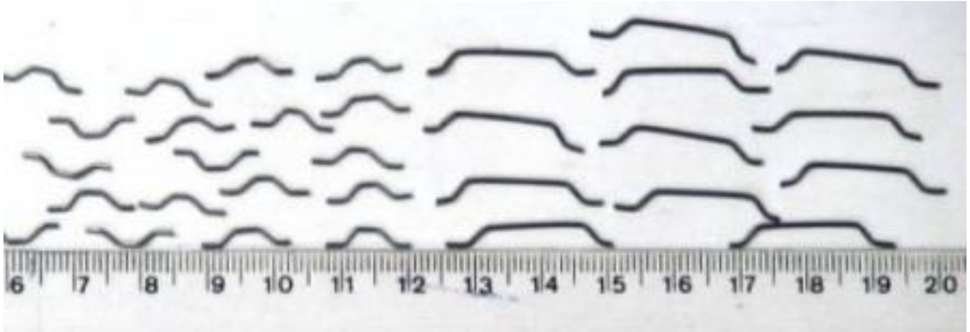


Figure 3. Steel microfibers (left) and conventional steel fibers (right)

3. RESULTS AND ANALYSIS

3.1. Compression tests in cylindrical test tubes

The values of the mechanical properties of the compounds are shown in Table 2: mean resistance to compression (f_{cm}), mean resistance to traction by diametrical compression ($f_{ctm,sp}$), and modulus of elasticity (E_{cs}).

Table 2. Average results of the characterization of the compounds on resistance to compression

Matrix	Phase	Group	Compounds	f_{cm} (MPa)	$f_{ctm,\,sp}$ (MPa)	E_{cs} (GPa)
Mortar (A)	I	1	CPA	52.5	3.1	23.8
		2	CPA1A	43.8	3.7	22.7
		3	CPA1.5A	42.2	3.7	23.1
		4	CPA2A	45.7	4.9	24.0
		5	CPA1.5A0.5C	49.2	4.4	28.2
		6	CPA1.5A1.5C	47.2	4.9	32.3
		7	CPA1.5A2.5C	43.6	4.8	31.0
		8	CPA1.5A3.5C	42.8	4.9	29.1
Micro-concrete (M)	I	9	CPM	62.3	3.8	35.2
		10	CPM1A	42.0	3.0	30.6
		11	CPM1A1C	40.6	3.7	26.3
		12	CPM1A2C	42.8	5.1	30.0
		13	CPM1A2.5C	20.8	2.8	19.9
	II	1	CPM1A1C	33.2	2.5	32.3
		2	CPM1A1.5C	30.6	2.2	31.0
		3	CPM1A2C	33.4	3.2	32.4
		4	CPM1.5A1C	28.3	2.6	29.8
		5	CPM1.5A1.5C	30.5	2.9	31.0
		6	CPM1.5A2C	29.2	2.4	30.2

3.2. Bending tests – loads and resistance

The tenacity of the compounds was determined following the recommendations of Rilem (2002), the results of which are those indicated in Table 3. The criterion for the evaluation of tenacity is based on the energy absorption capacity (P) *versus* the vertical displacement (δ).

According to Rilem, the contribution of the fibers on the tenacity of the compound is evaluated through the subtraction of the tenacity that comes from the response of the cementitious matrix. In Figure 4 we can observe the typical response of the behavior to flexion of compounds with fibers, along with the expressions used to calculate the equivalent resistances to traction in flexion ($f_{eq,2}$ e $f_{eq,3}$) and of the residual resistances during flexion ($f_{R,1}$ e $f_{R,4}$). The meanings of the parameters presented in that figure are:

- F_L – is the maximum *offset* strength within the δ=0,05 mm interval. This interval is obtained with the use of a parallel line to the initial tangent, going through the point that characterizes the displacement δ of the *offset*;
- δ_L – is the vertical displacement value that corresponds to F_L;
- $f_{fct,L}$ – is the tension that corresponds to the F_L force, given by the expression:

$$f_{fct,L} = \frac{3.F_L.L}{2.b.h_{sp}^2};$$

- L – is the free span of the test tube and b is its length;
- h_{sp} – distance from the top of the notch to the upper face of the test tube;
- D^b_{BZ}, $D^f_{BZ,2}$, and $D^f_{BZ,3}$ – energy absorption quota by the matrix and by the fibers, respectively. They are calculated through the area on the P-δ curve until specific displacements (see Figure 4);
- $F_{R,1}$ and $F_{R,4}$ – strength values corresponding to the δ_{R1}=0.46 mm and δ_{R4}=3.00 mm displacements. They are values used for the calculation of the residual resistances of the compounds.

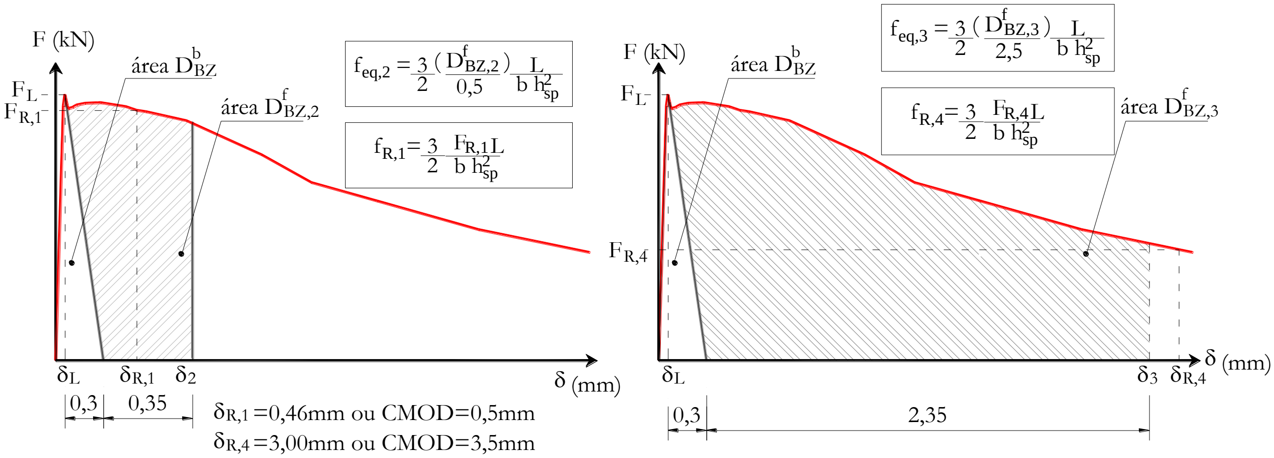


Figure 4 – Rilem (2002) criteria for the evaluation of the behavior of materials with fibers

Even according to the Rilem (2002), the quotas or tenacity parcels ($D^f_{BZ,2}$ and $D^f_{BZ,3}$) are transformed in equivalent flexural strengths ($f_{eq,2}$ and $f_{eq,3}$) for the different levels of displacement δ_2 and δ_3. The load capacity of the material in relation to a pre-defined arrow value is evaluated through the concept of residual flexural strength ($f_{R,1}$ and $f_{R,4}$).

Table 3 shows the value of the strength (F_M), which corresponds to the maximum strength reached by the compound throughout the load history.

Table 3. Loads and Resistance

Matrix	Phase	Compounds	Loads (kN)				Resistance (MPa)				
			F_L	F_M	$F_{R,1}$	$F_{R,4}$	$f_{fct,L}$	$f_{eq,2}$	$f_{eq,3}$	$f_{R,1}$	$f_{R,4}$
Mortar (M)	I	CPA	8.0	8.0	1.3	-	2.3	-	-	0.4	-
		CPA1A	13.4	13.4	12.5	5.2	3.9	3.3	2.6	3.6	1.5
		CPA1.5A	13.1	16.1	16.0	6.1	3.7	4.6	3.2	4.5	1.7
		CPA2A	14.5	17.6	17.4	7.6	4.6	5.5	4.2	5.5	2.4
		CPA1.5A0.5	16.4	17.8	17.2	9.3	4.6	4.9	4.0	4.8	2.6
		CPA1.5A1.5	16.0	21.0	20.9	9.4	4.8	6.5	4.8	6.3	2.8
		CPA1.5A2.5	22.1	23.7	23.5	12.8	6.1	6.5	5.0	6.5	3.6
		CPA1.5A3.5	20.0	21.4	20.8	6.1	5.5	5.7	3.8	5.7	1.7
Micro-concrete (M)	I	CPM	14.1	14.2	1.3	-	4.0	-	-	0.4	-
		CPM1A	12.0	12.1	7.5	3.7	3.3	2.0	1.6	2.1	1.0
		CPM1A1C	17.6	18.5	16.9	7.5	5.2	5.1	3.7	5.0	2.2
		CPM1A2C	19.4	21.9	19.7	8.0	5.5	5.7	4.1	5.7	2.3
		CPM1A2.5C	10.0	10.0	6.3	2.3	2.9	1.5	1.1	1.9	0.7
	II	CPM1A1C	12.2	14.3	11.4	1.0	3.6	3.5	2.4	3.4	0.3
		CPM1A1.5C	12.0	15.2	12.1	2.7	3.5	3.8	2.5	3.6	0.8
		CPM1A2C	14.4	18.9	15.9	1.8	4.1	4.9	3.0	4.5	0.5
		CPM1.5A1C	12.8	18.5	16.0	2.4	3.7	5.0	2.4	4.6	0.7
		CPM1.5A1.5	15.2	19.8	17.5	1.3	4.3	5.3	3.6	5.0	0.4
		CPM1.5A2C	11.0	15.6	13.4	3.2	3.2	4.4	2.9	4.0	1.0

It has been confirmed that the addition of steel fibers significantly contributes to the increase of the resistance defined by the parameter ($f_{fct,L}$), which represents the resistance quota of the compound that comes from the contribution of the cementitious matrix.

It is also possible to state that the addition of microfibers to the steel fibers resulted in even more significant improvements in this property for the mortar compounds in relation to the micro-concrete.

The performance of the mortar compounds from the contribution quota of the fibers ($f_{eq,2}$ and $f_{eq,3}$) was improved with the increase of the volume of fiber A and enhancing it with the addition of the steel microfibers.

For the micro-concrete compounds, the increase of the levels of equivalent flexural strength ($f_{eq,2}$ and $f_{eq,3}$) through the addition of steel micro fibers to fiber A is evident. In most those compounds, the strength ($f_{eq,2}$) exceeds the value of the strength ($f_{fct,L}$), showing significant strength gains after the cracking of the matrix.

3.3. P-CMOD Curves

The P-CMOD curves of the mortar compounds are shown in Figure 5. The presence of steel fibers and microfibers in the cementitious mortar matrix improved its behavior, translated in terms of an increase of the levels of strength, before and after the cracking of the matrix.

The increase in the volume of type "A" fibers provided a gradual improvement in the ductility of the mortar compounds. Similarly, the incorporation of the steel microfibers to the "A" fibers contributed even more in that sense.

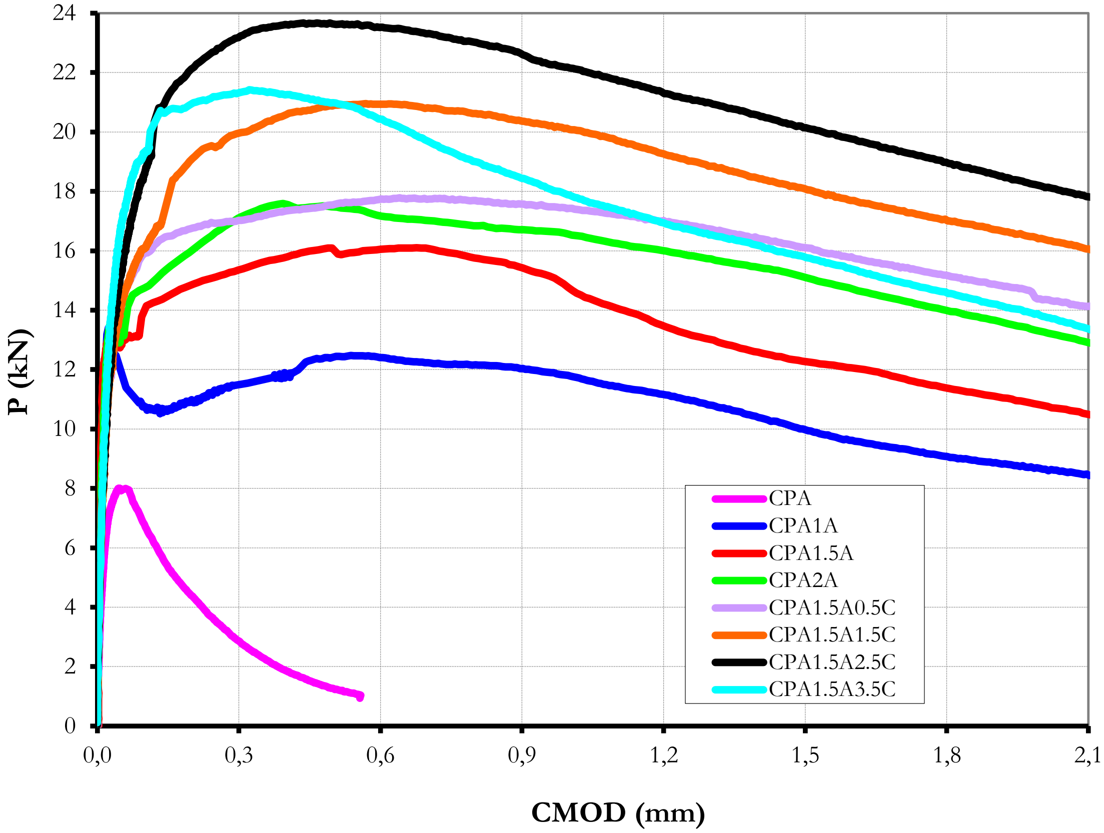


Figure 5. P-CMOD curves of the mortar compounds

The curves of the micro-concrete compounds are presented in Figure 6. The presence of fibers and microfibers primarily improved the energy absorption capacity of those compounds. The resistance capacity was decreased with the isolated presence of fiber A (CPM1A compound).

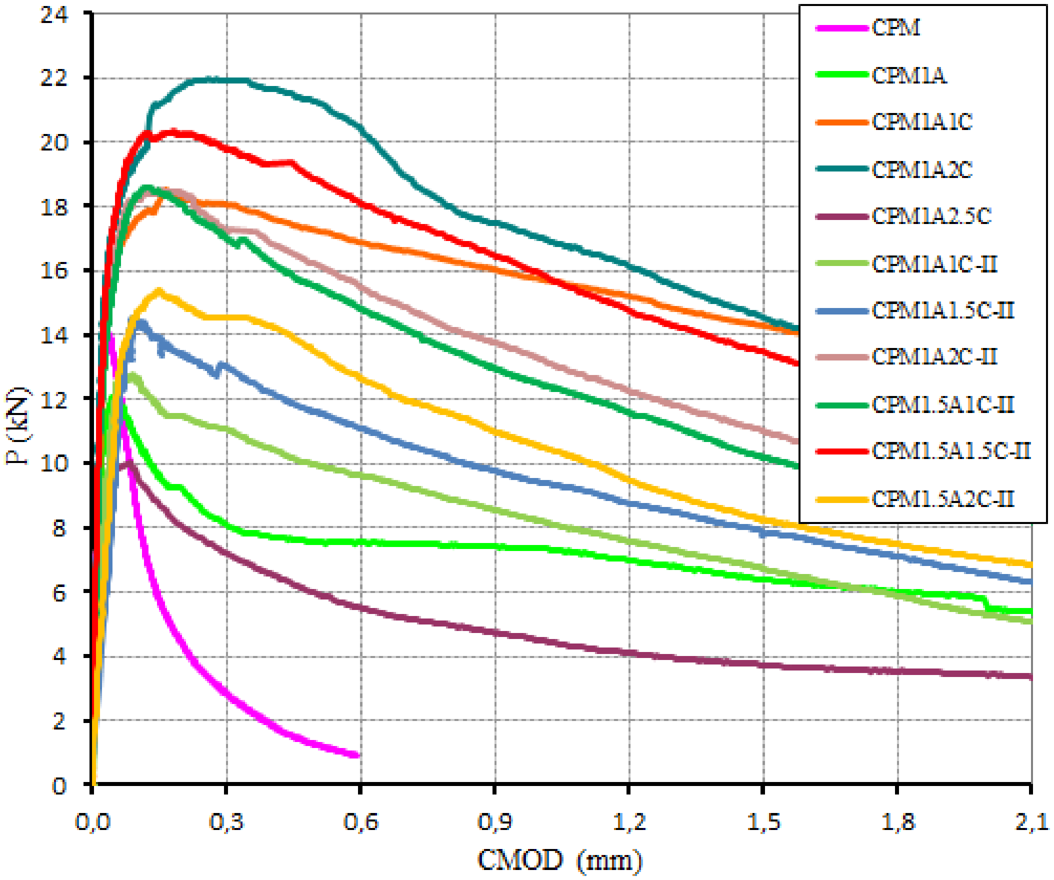


Figure 6. P-CMOD curves of the micro-concrete compounds

3.4. Fracture resistance curves

Figure 7 shows the fracture resistance curves of the mortar compounds. In Figures 8 and 9 the resistance curves of the compounds of the micro-concrete produced in phases I and II, respectively, are shown. Where “K_R” represents the resistance to the progress of the crack (resistance to the fracture of the compound) and “α” is the depth of the crack (a) relatively normalized to the height (W) of the test tube, i.e. $\alpha = a/W$.

The gain of resistance against cracking was mainly evidenced in the post-peak break regime (maximum strength), increasing between the different compounds with the increase of the range of metallic fibers incorporated to each one of them. With the exception of the CPA1.5A3.5C and CPM1A2.5C compounds, in which their resistances to fracture throughout the load history were inferior to those of the CPA1.5A2.5C and CPM1A2C compounds, respectively.

It is also possible to see that on the post-peak load phase, the final stretch of the resistance curve for the mortar compounds (CPA1.5A1.5C and CPA1.5A2.5C) and micro-concrete (CPM1A1C and CPM1A2C) are ascendant, which represents the high resistance gain to the propagation of the crack provided by the presence of the steel fibers and microfibers. This is associated to the energy dissipation of the pull-out process of the fibers and microfibers from the cementitious matrix.

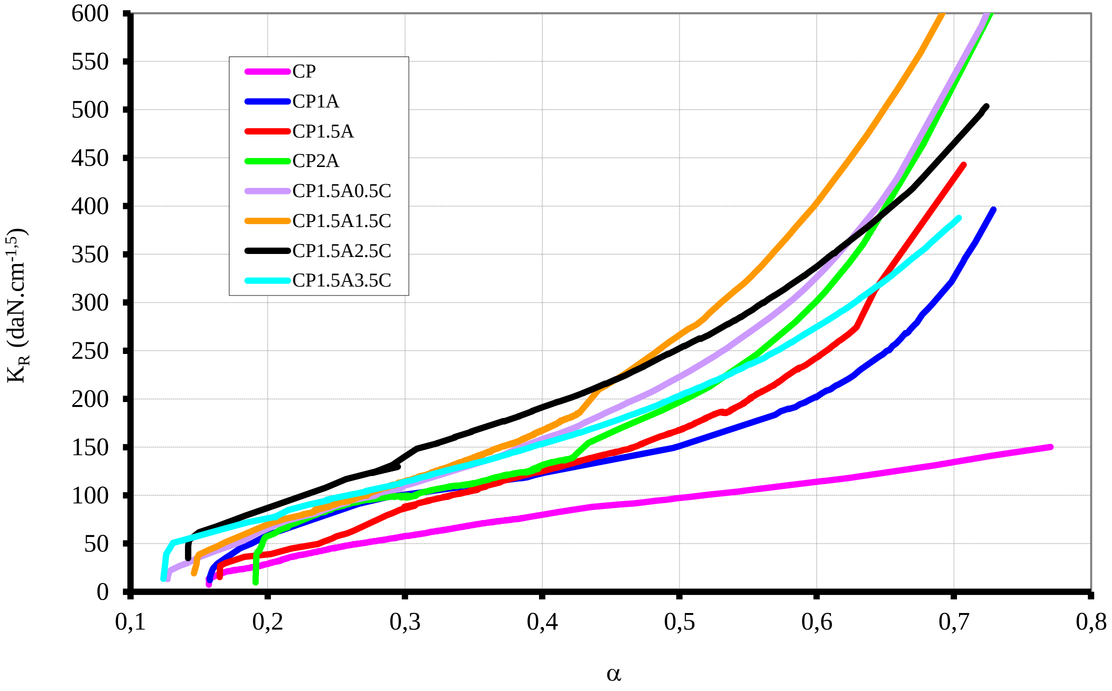


Figure 7. Fracture resistance curves of the mortar compounds

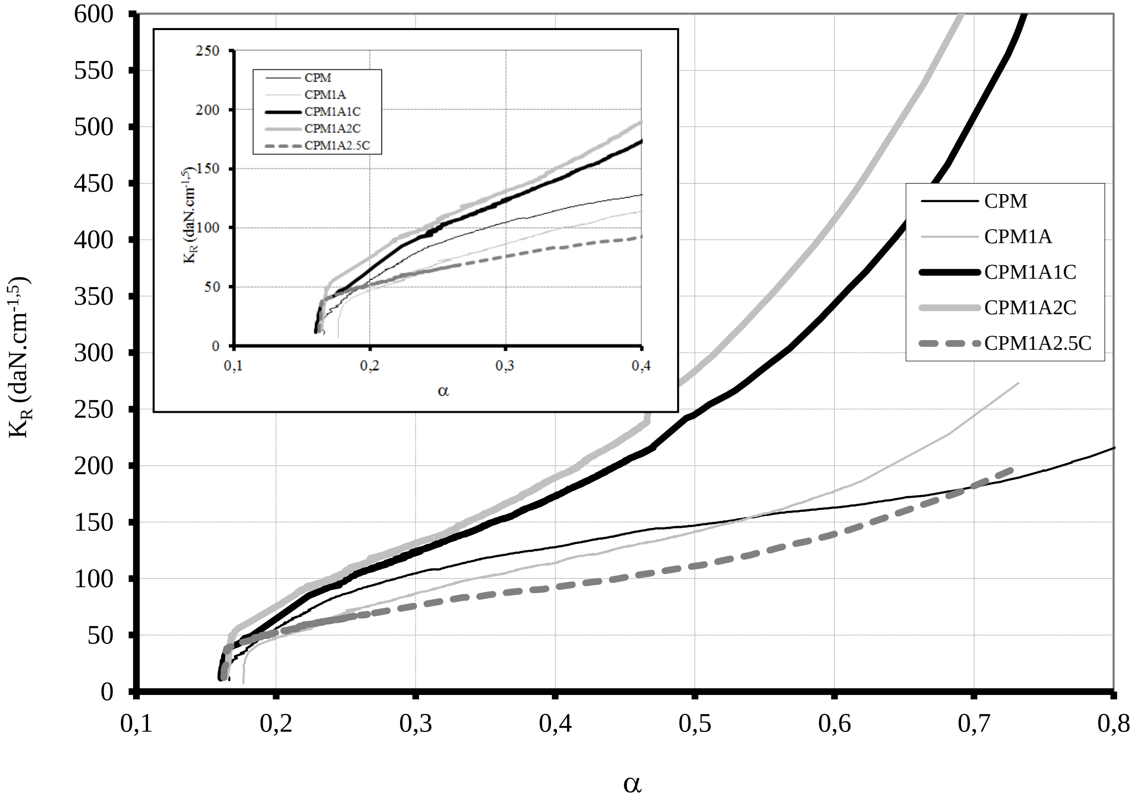


Figure 8. Fracture resistance curves of the micro-concrete compounds – Phase I

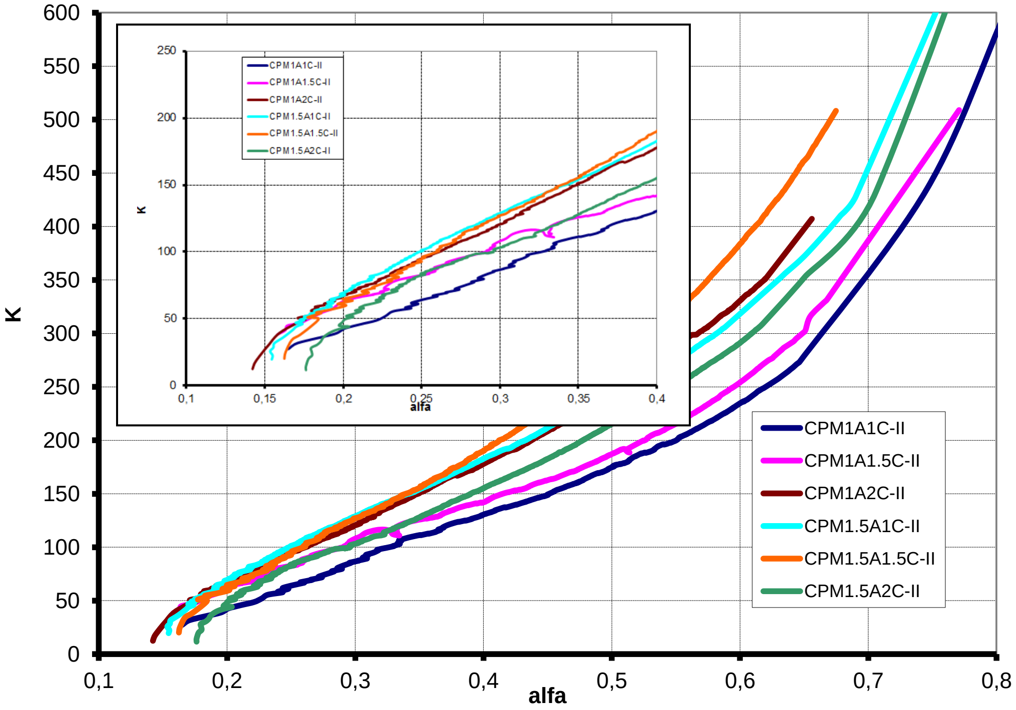


Figure 9. Fracture resistance curves of the micro-concrete compounds – Phase II

4. CONCLUSIONS

The following conclusions can be established based on the research done:

1. The hybridization process is an interesting alternative for the application in the recovery of the tensed concrete beam span, as the addition of steel microfibers to the short steel fibers increases the resistance to traction during flexion and increases the flexural tenacity of the mortar and micro-concrete compounds;
2. With the cracking of the matrix, the transfer of tensions was facilitated by the microfibers that, once dispersed in the matrix, conditioned the propagation of the crack to an increase of the load level of the compound;
3. Considering the pseudo-hardening characteristics and their specific application, the CPM1A2C compound was the one that presented the best properties among the ones produced in phase I;
4. Among the compounds produced in phase II, CPM1.5A1.5C-II stands out as it presented considerable increases in the maximum load through hybridization, as well as in the resistance to fractures and flexion.

5. REFERENCES

Ferreira, L. E. T., Bittencourt, T. N., Souza, J. L. A. O., Gettu, R. (2012), "*R-Curve behavior in notched beam tests of rocks"*, Engineering Fracture Mechanics, N. 32, pp 27-40.

Ferrari, V. J., Hanai, J. B. (2012), "*Flexural strengthening of reinforced concrete beams with carbon fibers reinforced polymer (CFRP) sheet bonded to a transition layer of high performance cement-based composite",* Ibracon Structures and Materials Journal, Vol. 5, N. 5, pp 596-626.

Arquez, A. P. (2010), Dissertaçao mestrado, "*Aplicación de laminado de polímero reforçado com fibras de carbono (PRFC) inserido em substrato de microconcreto com fibras de acero para reforço à flexión de vigas de concreto armado*", Escola de Engenharia de Sao Carlos, Universidade de Sao Paulo.

Rilem TC 162-TDF (2002). *Test and design methods for steel fibre reinforced concrete. Bending test,* Materials and Structures, Vol. 35, pp 579-582.