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Influence of steel fibers and mineral additions on cracking behavior of reinforced concrete tension members

Influência das fibras de aço e das adições minerais na fissuração de tirantes de concreto armado

L. A. OLIVEIRA JÚNIOR [a]
lualvaro@sc.usp.br

D. L. ARAÚJO [b]
dlaraujo@eec.ufg.br

R. D. TOLÊDO FILHO [c]
toledo@labest.coc.ufrj.br

E. M. R. FAIRBAIRN [d]
eduardo@coc.ufrj.br

M. A. S. ANDRADE [e]
masa@furnas.com.br

Abstract

In this work the influence of steel fibers and mineral additions (silica fume and fly-ash) on cracking behavior of reinforced concrete tension members was investigated. Hooked-end steel fibers with aspect ratio of 65 were used in volumes of 0.75%, 1.00% e 1.50%. Sixteen tension tests were performed in tension members 800 mm long with square cross section of 150 mm of side reinforced with single bar of CA-50 steel with diameter of 20 mm for determining crack widths. The results showed that steel fibers reduced the average crack width up to 75% and mineral additions improved cracking behavior of concrete. Crack widths were compared with suggested values by Brazilian, American and European recommendations, which were unsuitable for estimating crack width in steel fiber reinforced concrete.

Keywords: *tension specimen, reinforced concrete, steel fiber, cracking behavior, silica fume, fly-ash.*

Resumo

Neste trabalho é investigada a influência das fibras de aço e das adições minerais (sílica ativa e cinza volante) na fissuração de tirantes de concreto armado. Fibras de aço com gancho nas extremidades e relação de aspecto igual a 65 foram usadas nas frações volumétricas de 0,75%, 1,00% e 1,50%. Dezesseis tirantes de 800 mm de comprimento e seção transversal quadrada de 150 mm de lado reforçados com uma barra de aço CA-50 de 20 mm de diâmetro foram submetidos à tração axial para determinação das aberturas das fissuras. Os resultados mostraram que as fibras reduziram a abertura média de fissuras em até 75% e que as adições minerais melhoraram o comportamento do concreto na fissuração. As aberturas de fissuras foram comparadas aos valores sugeridos pelas recomendações das normas brasileira, americana e européia, que se mostraram inadequadas para estimar a abertura de fissuras em concretos reforçados com fibras.

Palavras-chave: *tirante, concreto armado, fibras de aço, fissuração, sílica ativa, cinza volante.*

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[a] *Universidade de São Paulo, Departamento de Engenharia de Estruturas, Escola de Engenharia de São Carlos, lualvaro@sc.usp.br, Av. Trabalhador Sancarlense, n. 400, São Carlos, SP, Brasil;*

[b] *Universidade Federal de Goiás, Programa de Pós Graduação em Geotecnia e Construção Civil, Escola de Engenharia Civil, dlaraujo@eec.ufg.br, Av. Universitária s/n, Praça Universitária, Goiânia, GO, Brasil.*

[c] *Programa de Engenharia Civil, COPPE, Universidade Federal do Rio de Janeiro, Instituto Alberto Luiz Coimbra de Pós Graduação e Pesquisa de Engenharia, Centro de Tecnologia, Bloco B, toledo@labest.coc.ufrj.br, Caixa Postal 68506, Rio de Janeiro, RJ, Brasil*

[d] *Programa de Engenharia Civil, COPPE, Universidade Federal do Rio de Janeiro, Instituto Alberto Luiz Coimbra de Pós Graduação e Pesquisa de Engenharia, Centro de Tecnologia, Bloco B, eduardo@coc.ufrj.br, Caixa Postal 68506, Rio de Janeiro, RJ, Brasil.*

[e] *Furnas Centrais Elétricas, Departamento de Apoio e Controle Técnico, Laboratório de Concreto, BR 153, km 1290, CEP 74001-970, Aparecida de Goiânia, GO, Brasil.*

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1. Introduction

Cracking is a nonlinear phenomenon which happens in plain and reinforced concrete structures and which can damage durability and using of these structures. Hence, after the cracking the material shows a nonlinear behavior that becomes more intense as the applied load increases.

In plain concrete, when the tensile strength is reached, cracks arise leading the material to collapse due to strain softening of plain concrete. However, when fibers are added to concrete, the material presents higher deformations before failure and dissipates high amounts of energy in this process. In fiber-reinforced concretes, the fibers concentrate stress in contact points between fiber and matrix, reducing stress at the crack tip and, hence, the velocity of cracks propagation, thus improving the cracking control process.

Cracking on concrete depends on the number of active cracks for dissipating the fracture energy. According to Noghabai [1], besides visible cracks, internal cracks also can be active and contribute for the dissipation of fracture energy. In plain concrete, only cracks dissipate fracture energy. However, in fiber-reinforced concrete, to the dissipated energy by cracks must be added the energy dissipated in pull out process of fibers. In this way, fiber-reinforced concrete always release amounts of energy higher than that released by plain concrete. This difference in dissipated amount of energy is related to the failure mode of both materials: brittle failure for plain concrete and ductile failure for fiber-reinforced concrete.

According to Ezeldin and Balaguru [2], the fibers also improve the bond between steel and concrete, both under monotonic and cyclic loadings, particularly after the concrete cracking. In concretes containing silica fume and fly-ach, these additions tend to improve more the bond in steel-concrete interface, reducing the splitting cracks which happen due to the high stress applied by the lugs of the reinforcement steel bars.

Another important aspect is related to the presence of mineral additions with pozzolanic activity on concrete, especially silica fume. Such mineral additions, by means of several mechanisms which are nod described here since they not are in the scope of this paper, tend to make the concrete less porous and therefore more dense and resistant. To this phenomenon is associated the increasing of the brittleness of concrete matrix, which become itself more breakable, in despite of its higher strength. Although, it is known of Technical Literature that in high strength matrices the adding of fibers is more beneficial than in normal strength matrices, mainly with respect to the capacity for energy absorption and cracking control.

1.1 Objective

This paper has the objective to assess the influence of steel fibers and mineral additions on cracking behavior of reinforced concrete.

1.2 Justification

This paper is part of a research project aims the using of steel fibers in spiral boxes at Power Stations and justifies itself by necessity of constraining to levels away those practiced in civil construction the cracking process in this kind of structure. In this meaning, steel fibers are a solution for the problem of cracking, since their great ability of delaying the arising and propagation of cracks on concrete. Also, the using of mineral additions in partial replacement of cement, particularly those with high pozzolanic activity, reduces the total cost of concrete because they are cheaper materials than cement.

2. Experimental program

2.1 Materials

In this experimental investigation, two typical matrices were produced: matrix made of Portland cement without mineral additions and matrix made of Portland cement with addition of 10% silica fume and 30% fly-ash, both with predicted compressive strength of 40 MPa at the age of 28 days. In production of these matrices were used a Portland cement type CP III 40 RS, according to Brazilian classification system for cements, coarse aggregate of granitic origin 25 mm maximum size, natural sand 4,75 mm maximum size, water, superplasticizer

Table 1 – Composition of concretes with and without mineral additions (kg/m^3)

Composition	Without mineral additions					With mineral additions				
	0.00%	0.00%*	0.75%	1.00%	1.50%	0.00%	0.00%*	0.75%	1.00%	1.50%
Cement	439.05	436.83	425.68	428.69	423.01	261.46	265.24	260.84	259.40	256.53
Silica fume	0.00	0.00	0.00	0.00	0.00	31.74	32.20	31.67	31.49	31.15
Fly-ash	0.00	0.00	0.00	0.00	0.00	100.43	101.88	100.19	99.64	98.54
Sand	870.10	873.67	849.37	857.38	846.02	871.53	884.13	869.46	864.66	855.11
Coarse aggregate	870.10	873.67	849.37	857.38	846.02	871.53	884.13	869.46	864.66	855.11
Water	173.50	172.70	167.24	168.82	166.58	172.28	174.77	171.20	170.25	168.37
Fiber	0.00	0.00	58.87	78.50	117.75	0.00	0.00	58.87	78.50	117.75
Superplasticizer	3.29	3.28	4.25	4.29	4.23	3.27	3.32	4.35	4.32	4.28

*Second casting.

Table 2 – Mechanical properties of studied concretes

Matrix	V_f (%)	f_{cm} (MPa) NBR 5739 (4)	$f_{ctm,sp}$ (MPa) NBR 7222 (5)	E_{cm} (GPa) NBR 8522 (6)
Without mineral additions	0.00	44.37	4.20	52.95
	0.75	56.90	6.15	38.93
	1.00	45.48	6.12	62.13
	1.50	52.17	8.28	52.37
With mineral additions	0.00	41.40	4.25	49.82
	0.75	44.37	4.73	44.90
	1.00	42.63	6.48	49.90
	1.50	49.90	7.09	69.10

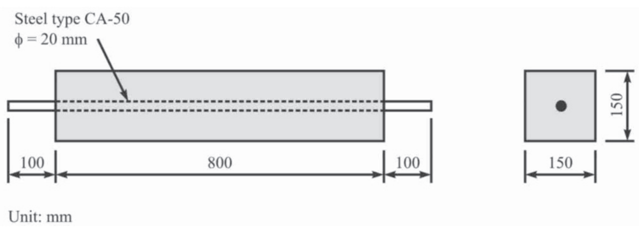
of third generation Glenium 3010, silica fume and fly-ash, both with pozzolanic activity verified by Oliveira Júnior [3]. In these concretes, the water/cement ratio was fixed on 0.40, although for concretes with mineral additions the water/cement ratio have been calculated in relation to the equivalent cement, that is, an mixture of cementitious materials which has the same density than cement. The workability of fresh concrete was controlled by adding of 1.00% of superplasticizer, except in plain concretes, in which the added amount of superplasticizer was 0.75%. to concretes with and without mineral additions were added steel fibers with hooked ends type DRAMIX RC 65/60 BN. The fibers was 60 mm long and 0.92 mm diameter and showed tensile strength of 1000 MPa and modulus of elasticity of 200 GPa. Fibers were used in amounts of 0.75% (58.8 kg/m^3), 1.00% (78.5 kg/m^3) and 1.50% (117.8 kg/m^3). Table 1 presents the composition of concrete used in casting of tension specimens.

Table 2 presents the average values of compressive and splitting tensile strengths and of modulus of elasticity of mixtures used in casting of tension specimens. These values were obtained considering results of two different castings.

2.2 Casting and storage of the specimens

Plain concretes (reference concretes) were produced in inclined axis mixer with capacity of 200 L while fiber-reinforced concretes were produced in vertical axis mixer with forced mixing with capacity of 500 L. The casting was carried out under controlled temperature and humidity. After the casting of concrete inside the forms the concrete was vibrated using vibrating needle. The specimens remained at the local where they were cast under the same temperature and humidity conditions in which the concrete was produced and cast from casting to hardening. After, the specimens were moved to the humid chamber, where they storage until the testing, when the concrete was 28 days old with 95% minimum humidity and temperature around 20 ºC.

Figure 1 – Characteristics of tension specimens used in tensile tests



2.3 Tension specimens

Sixteen tension specimens were produced for tensile tests. They were 800 mm long and 150 mm side square cross-section (see Figure 1). They were reinforced with a single steel bar type CA-50 20 mm diameter and presented yielding strength of 494 MPa and modulus of elasticity of 210 GPa.

2.4 Testing procedure

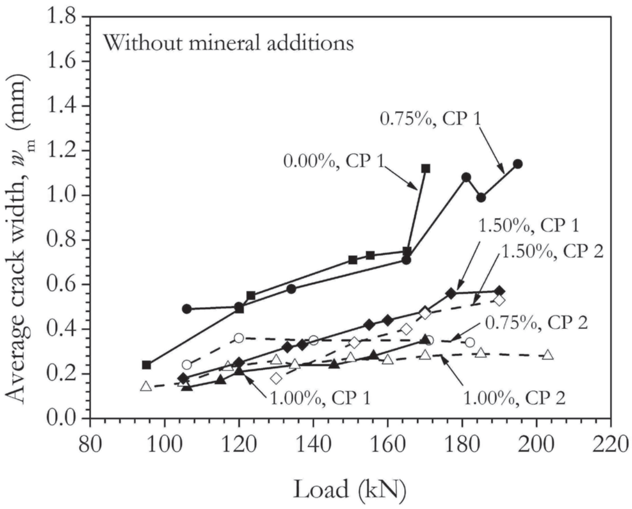
Tension specimens were tested in a servo-hydraulic machine under displacements control. The displacement ratio adopted in the tests was 0.30 mm/min. During the tests, crack width was measured by a fissuremeter with accuracy of 0.02 mm. Crack width was measured in intervals of 10 kN and for each new crack arisen. In each measurement, the width of all cracks was measured in many points in a given crack, thus being determined the average width for each crack. The analysis was based on the average main crack width, that is, the wider crack. The test was performed until the loading reaches 200 ± 5 kN.

3. Results and discussion

3.1 Crack opening

In Figure 2 are presented the average values of main crack width, measured in tension specimens with different amounts of fibers and without mineral additions, with respect to supported load by tension specimen. The maximum measured crack width was 1.12 mm for tension specimens without mineral additions and 1.56 mm for tension specimens with mineral additions.

Figure 2 – Average main crack width for mixtures without mineral additions



The maximum crack width observed in the final of the test varied from 0.28 mm to 1.14 mm with respect to amount of fibers added to the matrix. This variation corresponds to decreasing of up to 75% in comparison with the maximum crack width measured in tension specimens made of plain concrete. As expected, it was observed that cracking decreases as amount of fiber increases due to the better cracking control process provided by fibers when these are added in high amounts. The tension specimen CP1 made of concrete reinforced with 0.75% of fibers showed considerable increasing on its crack width. However, this was an isolated case, once the specimen CP2 of the same concrete showed satisfactory results.

Figure 3 shows the average main crack width, measured in specimens made of concrete with mineral additions, with respect to the supported load by tension specimens. The maximum crack width varied from 0.36 mm to 0.87 mm as the fiber amount was increased, which represents a reduction of 77% on the crack width in relation to the average value obtained for plain concrete. The obtained values showed high scattering, but, in general, the crack width decreased as the fiber amount increased.

It is important to emphasize that the path followed by the crack is random and that measured values for crack width were not measured at the same point. The values presented in these figures are related to the mean of readings done in several points of the crack (preferentially in the corners), what it means that crack width is not uniform along its path, especially in fiber-reinforced concrete.

During casting, reinforcement steel bar may suffer little deviations in relation to its initial position, be by casting of concrete inside the forms or by vibration. The effects of the eccentricities caused by these little deviations are significant when the load reaches high values, generating flexure stresses on tension specimens. The occurrence of tension stresses caused by flexure on tension specimens justifies the reductions on the crack width for determining the levels of loading.

Vibrations also can affect the values of crack width of tension specimens made of fiber-reinforced concrete when it affects the distribution of fibers on matrix. Soroushian and Lee [7] investigate the variation of the number of fibers per unit of cross section area and they concluded that there is a higher concentration of fibers at the bottom of the form than at regions near to the concrete surface. From the surface towards to the bottom, the fiber orientation factor, according to Soroushian and Lee [7], increased in 28%. However, this increasing did not have significant statistical effect on the number of fibers per unit of area. Despite of this fact, Soroushian and Lee [7] concluded that vibration seems to change the fiber orientation factor, tending to align them in horizontal planes.

Despite of the scattering observed in the readings of crack width and factors which may influence the reading, it can be easily noticed in Figures 2 and 3 that addition of fibers reduced significantly the crack width. Comparing the maximum limit of crack width established by the NBR 6118 [8] of 0.40 mm for structures with environmental aggressively class I, it can be observed that for plain concrete this limit was reached for a slightly higher load than the first crack load. In tension specimens of fiber-reinforced concrete, this limit was reached for loads near to the yielding load and, in some cases, it neither was reached.

The experimental values of the average main crack width were compared to values calculated by recommendations of NBR 6118 [8], do ACI 224R [9] e do Eurocode 2 [10]. From Figure 4 to Figure 6 it is showed a graphical comparison between experimental and obtained by these recommendation values. In the expressions of recommendations, the tensile strength and modulus of elasticity obtained experimentally for each tension specimen were used. These values are presented in Table 2. The value assumed for the modulus of elasticity of steel was 210 GPa.

Figure 4 compares experimental values of average main crack width with values obtained by applying Brazilian recommendation. In this case, the two criterions of that recommendation were used. From this comparison, it was observed that equations proposed in that recommendation were not suitable for evaluating

Figure 3 – Average main crack width for mixtures with mineral additions

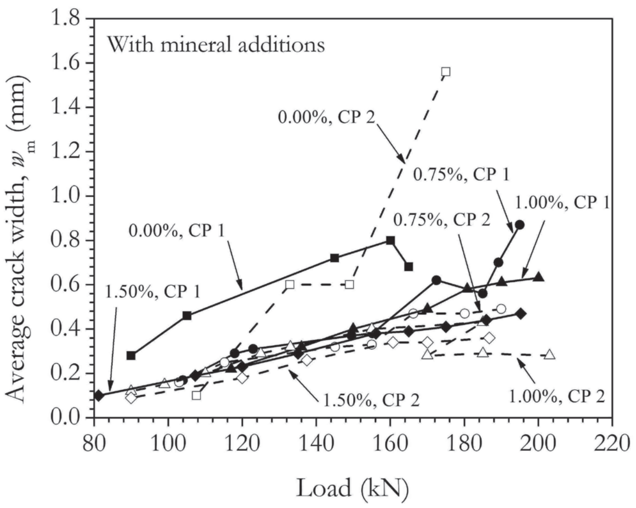
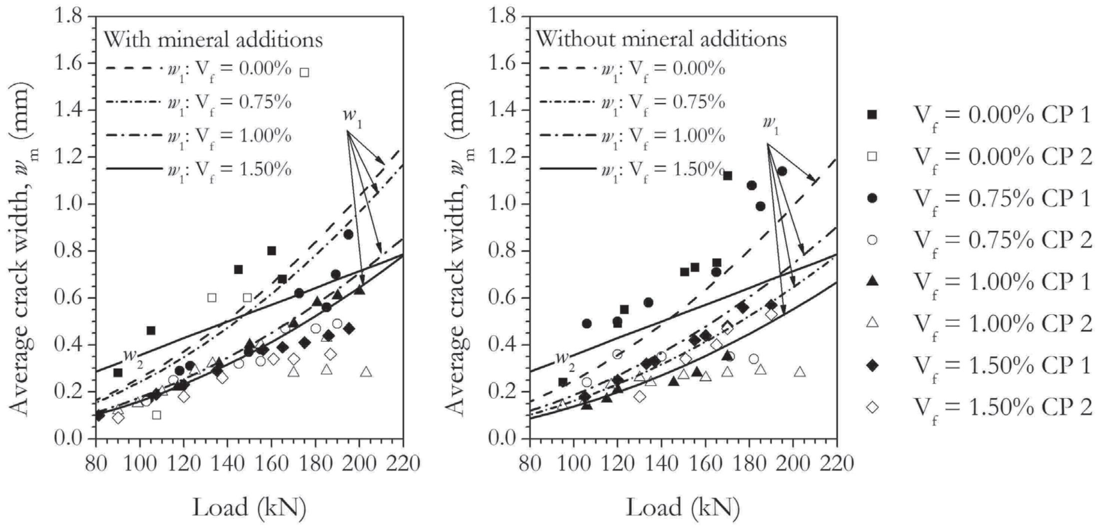


Figure 4 – Average main crack width – comparison between experimental and calculated according to NBR 6118 values for concretes with and without mineral additions



the crack width, once the obtained values were systematically lower than values measured during the tests and the scattering of results was similar to the crack width (the order of tenths of a mm).

According to Almeida [11] the equation of the Brazilian recommendation NBR 6118 which provides the value of w1 (equation 1) does not consider the influence of the concrete cover on the cracking behavior, because it assumes a constant relationship between concrete cover and reinforcement steel bar diameter. In case of equation which provides the value w2 (equation 2), Almeida [11] reports that are not considered the influences of reinforcement steel bar diameter and the area of concrete encasing reinforcement steel bar, of concrete cover and of curvature of the structural element (in case of bent elements). All these factors justify the difficulties of mentioned expressions in evaluating reliable values of crack width.

Figure 5 – Average main crack width – comparison between experimental and calculated according to Eurocode 2 values for concretes with and without mineral additions

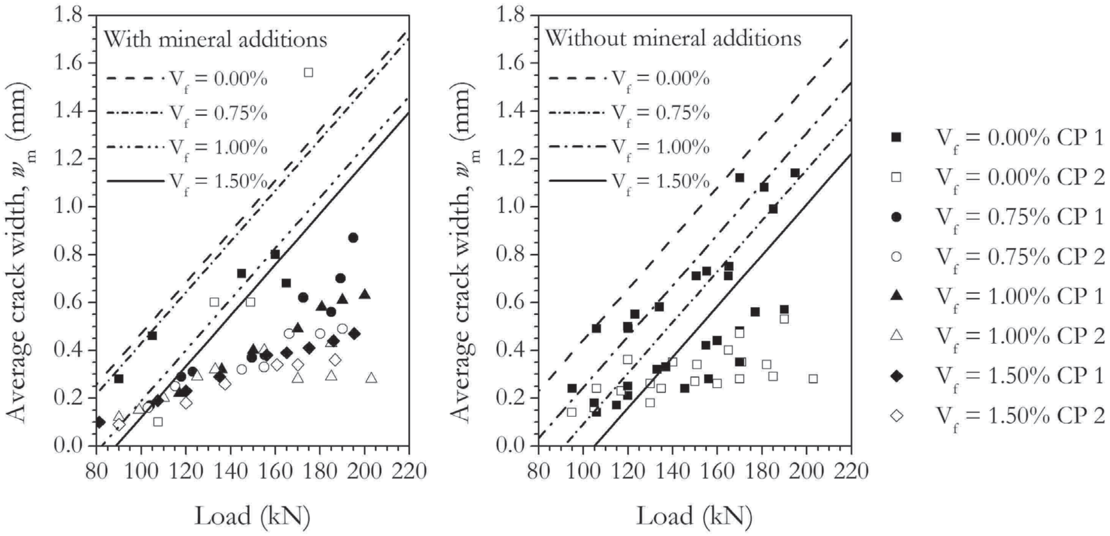
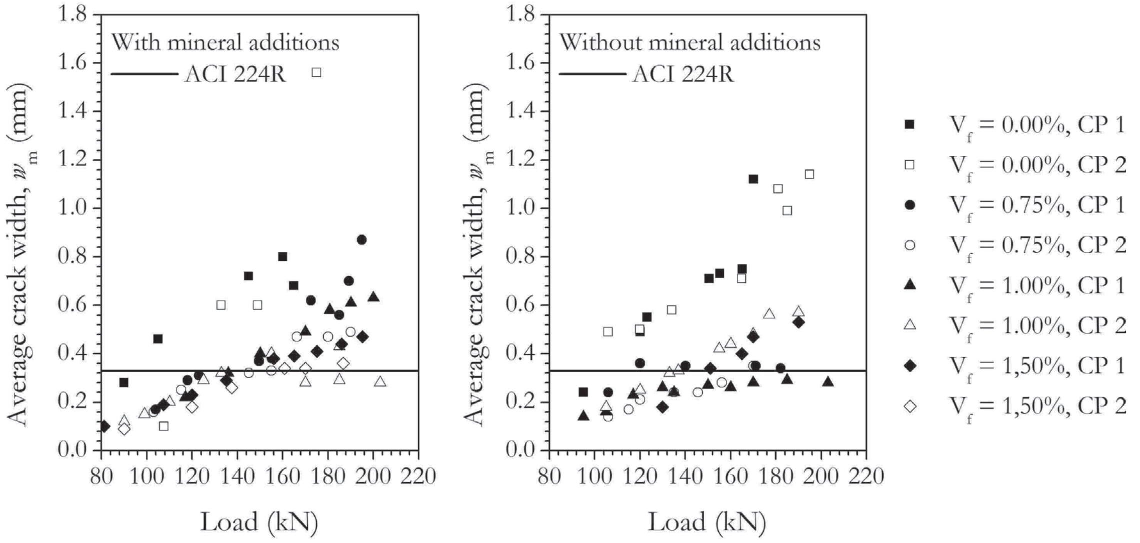


Figure 6 – Average main crack width – comparison between experimental and calculated according to ACI 224R values for concretes with and without mineral additions



$$w_1 = \frac{\phi}{12{,}5\eta}\frac{\sigma_s}{E_s}\frac{3\sigma_s}{f_{ctm}} \qquad (1)$$

$$w_2 = \frac{\phi}{12{,}5\eta}\frac{\sigma_s}{E_s}\left(\frac{4}{\rho}+45\right) \qquad (2)$$

in which w_1 and w_2 are the crack widths, ϕ is the reinforcement steel bar diameter, η is the coefficient of superficial conformation of the reinforcement steel, σ_s and E_s are the stress and modulus of elasticity of reinforcement steel, f_{ctm} is the average tensile strength and ρ is the reinforcement ratio.

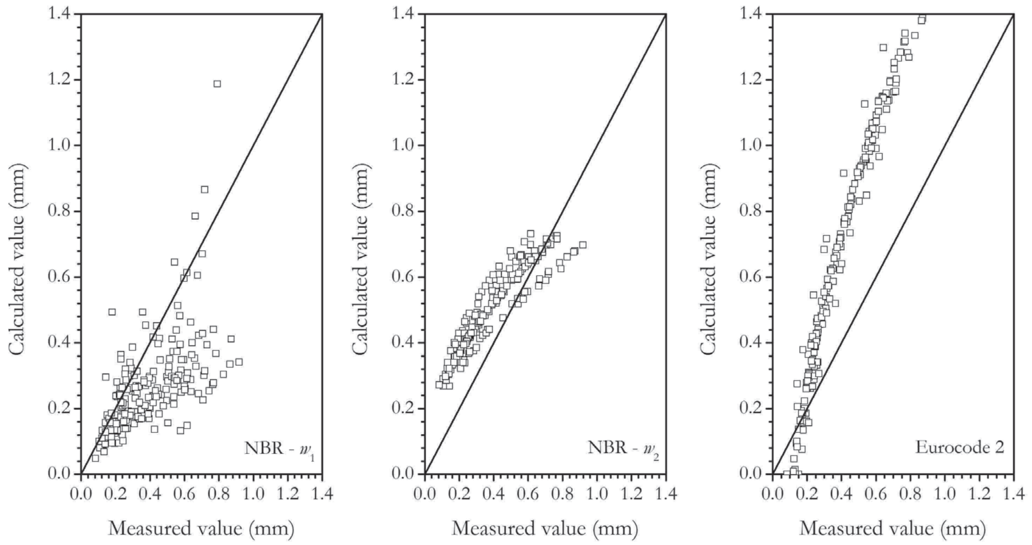
In tension specimens made of fiber-reinforced concrete, it was observed that equations of Brazilian recommendation were not suitable for evaluating the crack width, as expected, taking into account that such equations were not originally developed for this kind of material.

Figure 5 compares experimental values of crack width of tension specimens made of concretes with and without mineral additions to values calculated according to recommendation of Eurocode 2 [10]. It was observed, in general, equation proposed by Eurocode 2 [10] is reasonably well approximated the experimental values of tension specimens made of plain concrete. This happened due to the consideration of crack width as a linear function of reinforcement steel stress, which is a simplification towards to safety, once, even in service, reinforcement concrete structures does not behave linearly. In tension specimens made of fiber-reinforced concrete, especially those with high amounts of fibers, the theoretical values were higher than ones observed in the tests, which make evident the difficult of proposed equation by Eurocode 2 [10] in evaluating the crack width for fiber-reinforced concrete. This is natural, once the proposed equation was developed just for plain concrete. This behavior was observed on tension specimens with and without mineral additions.

Figure 6 compares experimental values of crack width of tension specimens made of concrete with and without mineral additions to values calculated using ACI 224R [9] recommendation. It was observed, in general, the ACI 224R [9] recommendation for evaluating crack width was not suitable for fiber-reinforced concrete, because, like Brazilian and Eurocode recommendations, such recommendation was developed only for plain concrete. The equation of ACI 224R [9] recommendation was developed based on the reinforcement ratio, on the concrete cover and on the stress equivalent to 40% of the reinforcement steel yielding stress. In this way, it is always obtained a constant value of crack width, independently of the level of stresses on the reinforcement steel or of the crack stage reached. These considerations make equation of ACI 224R [9] not suitable for evaluating satisfactorily crack width, especially for fiber-reinforced concrete, for which the mentioned equation was not developed.

The comparison between experimental and theoretical values of crack width on tension specimens with and without mineral additions is emphasized in Figure 7, which demonstrates that the value of crack width calculated by expression of w_1 of Brazilian recommendation was higher than the experimental value and lower than that when the calculated value is obtained by expression of w_2 of Brazilian recommendation and Eurocode 2. The graphs are merely illustrative and are not susceptible to correlations, because they do not consider the differences between plain and fiber-reinforced concretes. In graphs of Figure 7, the points represent experimental results and the line represents the equality between theoretical and

Figure 7 – Comparison between experimental and calculated according to Brazilian and European recommendations values of crack width



experimental values. The ACI 224R recommendation calculates the crack width for a stress equivalent to 40% of reinforcement steel yielding stress, then, how crack width were not measured in this stress level, the comparison between experimental and theoretical according to ACI 224R are not justified in this case.

3.2 Spacing between cracks

In tension specimens made of plain concrete, is easy to determine the maximum spacing of crack, once the cracks generally arise in the four faces of tension specimens. Nevertheless, this do not happen in tension specimens made of fiber-reinforced concrete. Due to the multiple cracking, it is common the occurrence of cracks in just one face of tension specimen, mainly when high amounts of fibers are used. Besides, sometimes cracks arise from other cracks and make branches, which difficult even more the identification of maximum spacing of cracks. Taking into account these aspects, it is necessary establish criterions to determine the maximum spacing between cracks on fiber-reinforced concrete.

Table 3 shows the maximum values of spacing between cracks for tension specimens made of plain and fiber-reinforced concrete. The values showed in this table, related to fiber-reinforced concrete, correspond to the higher spacing observed between two adjacent cracks which occur in, at least, two faces of tension specimens.

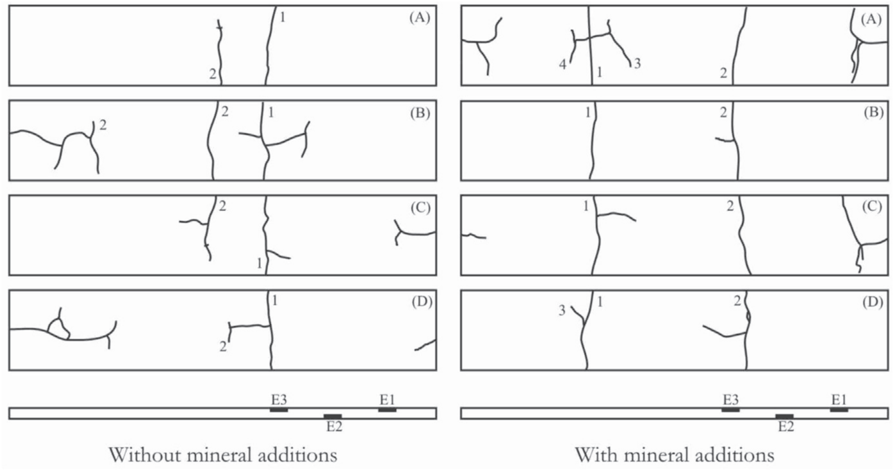
Analyzing that table it was observed, in general, the spacing between cracks was reduced with adding of fibers, which one more time confirm the benefits provided by adding of fibers to concrete, between them the reduction of the anchorage length of reinforcement steel bars. It is also observed, that tension specimens made of plain concrete with mineral additions showed the highest values of spacing between cracks, what indicates a worsening of the bond in steel-concrete interface and a higher crack width. These aspects are confirmed by Figures 2 and 3. However, it seems there not to be influence of mineral additions over the spacing between cracks on fiber-reinforced tension specimens, even with a little increasing on the crack width due to the mineral additions had been observed.

Analyzing the influence of fiber amount on the maximum spacing between cracks, it was observed the impossibility of establishment

Table 3 – Maximum spacing between cracks (mm)

V_f (%)	Without mineral additions		With mineral additions	
	CP 1	CP 2	CP 1	CP 2
0.00	213	-	275	-
0.75	103	116	167	173
1.00	197	156	149	130
1.50	154	161	100	106

Figure 8 – Final crack patterns in four faces of plain concrete tension specimens



of a clear relationship between crack spacing and fiber amount, what is due to the random nature of paths followed by cracks during their development and to the introduction of subjectivity with the establishment of criterions without mathematical basement.

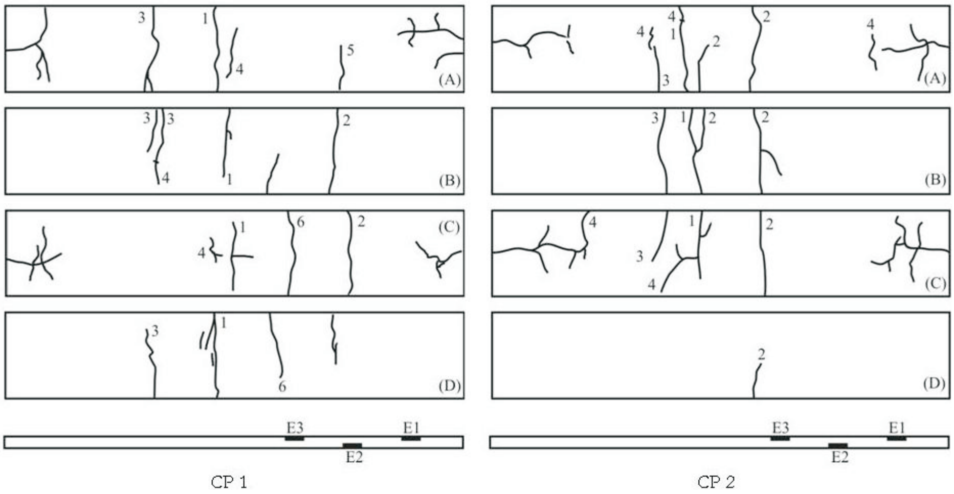
3.3 Crack patterns

The final crack patterns for plain concrete tension specimens, presented in Figure 8, reveal two transversal cracks which were more spaced on tension specimen made of concrete with mineral additions, what suggest a worsening of the bond between steel and concrete. After main crack formation (cracks 1 and 2), cracks arose in three faces of tension specimen made of plain concrete without mineral additions and in four faces of tension specimen made of plain concrete with mineral additions, both nearly at the middle of the cross section width, in which splitting cracks were observed, as shown by Figure 9. Other aspect noticed was the branching of splitting cracks, which reduced tension stiffening of concrete. Nev-

Figure 9 – Aspect of splitting cracks on the cross section

Figure 10 – Shear cone originated from reinforcement steel pull out process

Figure 11 – Final crack patterns in four faces of tension specimens made of concrete without mineral additions reinforced with 0.75% of fibers



ertheless, Abrishami and Mitchell [12] verify that splitting cracks does not have significant deleterious effects when the concrete cover/reinforcement steel bar ratio is lesser then 2.5. Thus, splitting cracks must not have influenced the obtained response, since for tested tension specimens that ratio was 3.25. It was observed the formation of a shear cone due to the reinforcement steel pull out process with one crack surrounding reinforcement steel bar (see Figure 10), a typical characteristic of this process.

In fiber-reinforced concrete tension specimen, the shear cone also was created, but without presents that typical crack of shear cone. That failure mode indicates that the chosen sizes for tension specimens should have been lesser, as the steel bar diameter should have been lesser. Nevertheless, the fiber length (60 mm) and reinforcement steel bar diameter (25 mm) limited sizes of tension specimens to avoid fiber alignment.

Adding of fibers to concrete changes completely the crack patterns, as it can be observed from Figure 11 to Figure 16. In these figures, it was observed the multiple cracking caused by steel fibers, which contributed with reducing of crack width. As consequence of the multiple cracking, it has increasing of the number of fibers which reflects on reducing of spacing between them. Splitting cracks were not avoided, but they were concen-

Figure 12 – Final crack patterns in four faces of tension specimen made of concrete without mineral additions reinforced with 1.00% of fibers

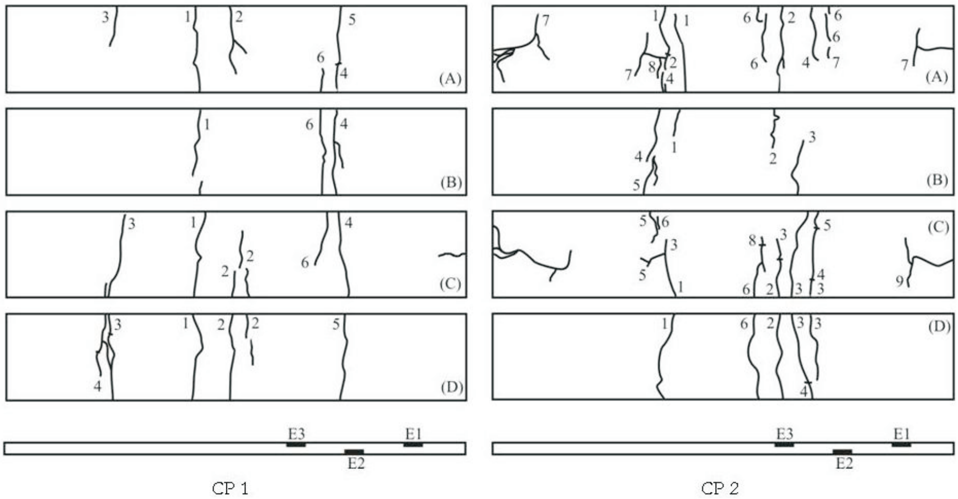
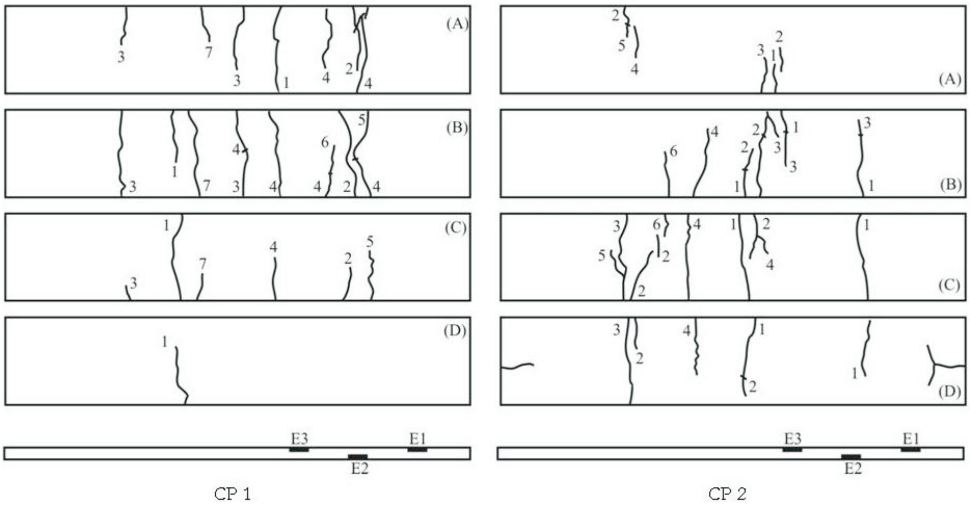


Figure 13 – Final crack patterns in four faces of tension specimen made of concrete without mineral additions reinforced with 1.50% of fibers



trated at the edges of tension specimens in most cases. Besides, the presence of silica fume and fly-ash seems to have aided in crack control by means of improving of fiber-matrix and steel-concrete bonds, resulting in improving of the tension specimen global response.

Positive influence of steel fibers on the cracking behavior was evidenced by the number of cracks, which increased highly with adding of fibers to concrete. This increasing, in general, was higher in concretes reinforced with high amounts of fibers and without mineral additions. No explicit relationship between the fiber amount and the number of visible crack was observed for concretes containing mineral additions, what is probably due to the scattering observed on the number of cracks. Apparently the fiber aspect ratio did not influence the number of visible cracks.

4. Conclusions

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

1. It was observed that steel fibers reduced the average crack width for concretes without mineral additions in up to 75%. In case of concretes with mineral additions, that reduction

Figure 14 – Final crack patterns in four faces of tension specimens made of concrete with mineral additions reinforced with 0.75% of fibers

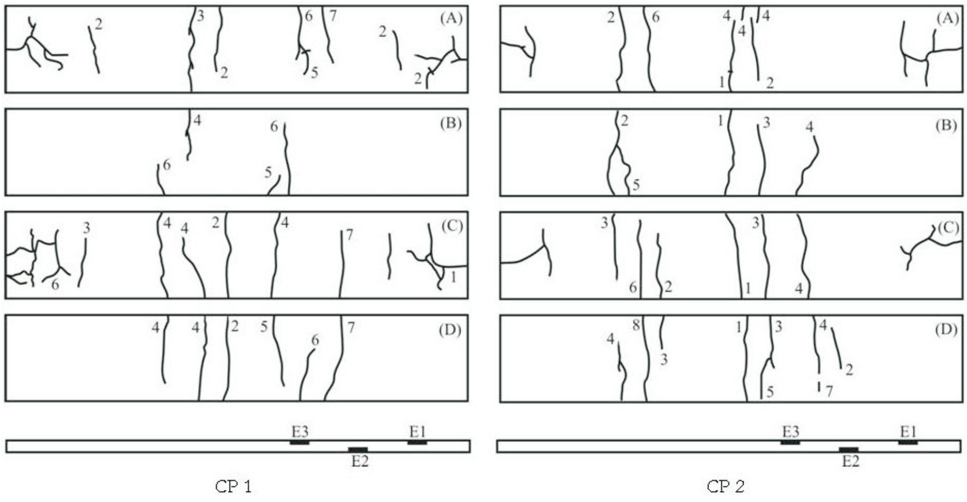
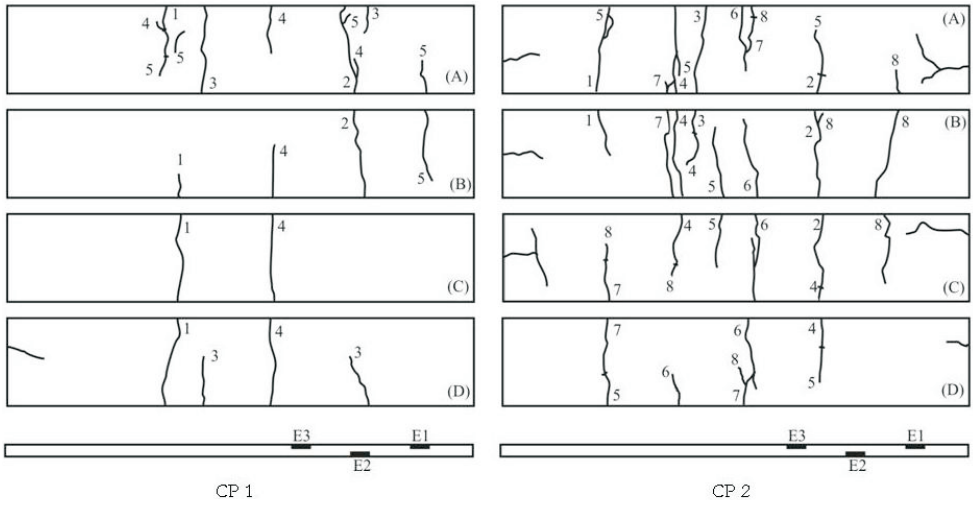


Figure 15 – Final crack patterns in four faces of tension specimens made of concrete with mineral additions reinforced with 1.00% of fibers



was of up to 77%. This fact shows that mineral additions did not influence significantly the crack width;

2. The maximum spacing between cracks was reduced as fiber amount was increased. However, a relationship between crack spacing and fiber amount was not clear due to the multiple cracking of the matrix and to the fact of cracks can arise in any point of tension specimen, what introduces high scattering on average values of spacing between cracks;
3. The evaluation of crack width by means of recommendations (NBR 6118, ACI and Eurocode 2) showed that such recommendations cannot be applied to fiber-reinforced concrete structures. The principal reason for this fact is the origins of mentioned recommendations, which were developed from tests carried out in plain concrete tension specimens and, thus, does not allow considering the influence of fibers;
4. The presence of steel fibers caused multiple cracks on concrete, which contributed to increasing of tension stiffening of concrete. This increasing was more pronounced in concretes containing high amounts of fibers.

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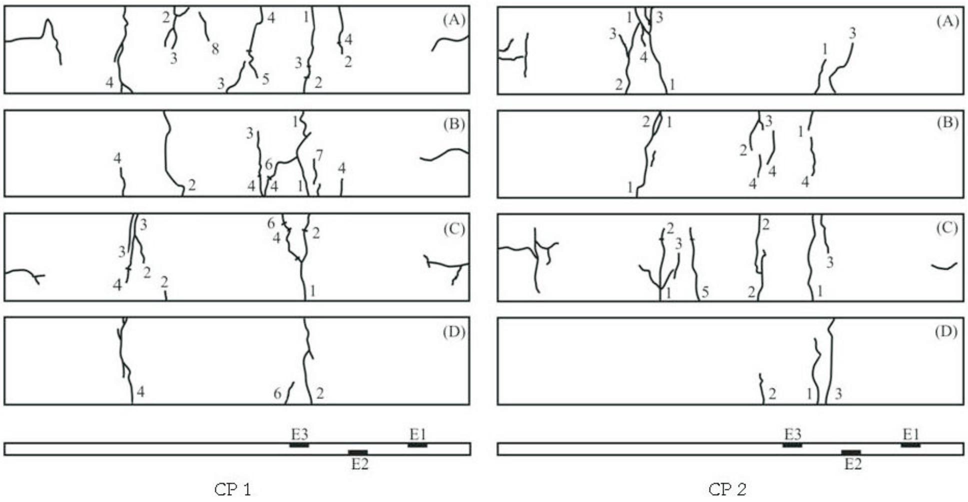
Figure 16 – Final crack patterns in four faces of tension specimens made of concrete with mineral additions reinforced with 1.50% of fibers



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