Evaluation of early age cracking in rendering mortars with polypropylene fibers

Avaliação da fissuração em baixas idades de argamassas de revestimento com fibras de polipropileno

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Abstract

The incorporation of fibers in concrete produces an improvement in the characteristics of the material as observed in different studies. In order to obtain the same good results, fibers are added to rendering mortars to reduce some of their drawbacks. However, this type of mortar has some specific characteristics, such as hydrated-lime utilization or higher air, which is not usual in concrete. Thus, this study aims to evaluate the potential of polypropylene fibers to reduce early age cracking caused by restrained shrinkage in rendering mortars. Two types of mortars were used to verify possible differences in the way they responded to the introduction of fiber. The influence of the fiber content was also investigated. Mortars were evaluated in fresh state, and mechanical behaviors were measured at several ages. The restrained shrinkage cracking was followed for 21 days using the ring test method. The use of polypropylene fibers leads a smaller value of total crack width and a delay of the first crack. Also, the elastic modulus shows a higher correlation with the mortars crack width. Both parameters were successfully used to predict the mortars crack width. The ring test method may be a suitable test method to evaluate the capacity of fibers to control the crack formation in rendering mortars.

Keywords: Rendering mortar. Polypropylene fiber. Cracking. Mechanical strength. Ring test.

Resumo

A utilização de fibras no concreto resulta na melhora de algumas características como já foi confirmado por muitos estudos. Buscando obter os mesmos bons resultados, as fibras vêm sendo utilizadas em argamassas para revestimentos, reduzindo algumas desvantagens deste material. Porém, essas argamassas têm características específicas como a utilização de cal hidratada ou maiores teores de ar, que não são usuais no concreto. Portanto, esse trabalho tem como objetivo avaliar o potencial das fibras de polipropileno para reduzir a fissuração a curtas idades causadas pela retração restringida em argamassas de revestimento. O programa experimental foi conduzido com dois tipos de argamassas para revestimento e três teores de fibras. Com essas variáveis se pretende verificar se a introdução das fibras resulta comportamento distinto em função da diferença nas matrizes. As argamassas foram avaliadas no estado fresco e o comportamento mecânico foi medido em várias idades. A fissuração por retração restringida foi acompanhada até os 21 dias utilizando o ensaio do anel. Os resultados mostraram que o uso de fibras de polipropileno resultou em menores aberturas e atrasaram a ocorrência da primeira fissura. Além disso, o módulo de elasticidade mostrou elevada correlação com a abertura de fissura. Esses parâmetros foram utilizados para a predição da abertura de fissura das argamassas. O ensaio do anel pode ser um método de ensaio adequado para avaliar fibras para o controle da fissuração em argamassas para revestimento.

Palavras-chaves: *Argamassa de revestimento. Fibra de polipropileno. Fissuração. Resistência mecânica. Ensaio do anel.*

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Introduction

Mineral binder mortars applied to external masonry walls are the most popular constructive solution for renderings in Brazil. These renderings are used mainly to protect buildings from external actions. If the renderings crack, their performance will be seriously compromised. The main causes of cracking in renderings are thermal and shrinkage deformations. Early age shrinkage of cementitious matrices is the result of several complex physico-chemical phenomena.

One solution that is being considered to reduce the effects of plastic shrinkage in cement-based materials is the use of small contents of synthetic fibers. Several studies have been carried out on this topic (SANJUAN; MORAGUES, 1997; MESBAH; BUYLE-BODIN, 1999; ALY; SANJAYAN; COLLINS, 2008; PEREIRA-DE-OLIVEIRA; CASTRO-GOMES; NEPOMUCENO, 2012). However, most of these studies focus on concrete application or high strength mortars. Rendering mortars have some specific characteristics, such as the use of hydrated lime or higher air content, that have not been considered in these studies. Some studies focused on rendering mortars evaluated the influence of fibers on fresh state characteristics, mechanical behavior and rendering adherence (MONTE; SILVA; BARROS, 2009; MONTE; BARROS; FIGUEIREDO, 2012; PEREIRA-DE-OLIVEIRA; CASTRO-GOMES; NEPOMUCENO, 2012). The amount of fiber used in rendering mortars are mainly limited by rheological conditions and it is difficult to find applications of contents above 1%.

The effects of shrinkage in mortars depend on a number of factors, including the curing conditions, raw materials, mortar lining thickness and the level of strain restriction. In addition, the evaluation results, including their magnitude, can be influenced by the characteristics of the test methods. Many test methods are available to evaluate restrained shrinkage in cementitious systems. Bentur and Kovler (2003) classified the tests into four categories, i.e., ring, plate, longitudinal and substrate restrained. These authors mention the use of ring tests for comparative purposes, for example, to evaluate the efficiency of fiber addition to reduce cracking sensitivity. The ring test is a test method that enables to evaluate the cracks in terms of maximum and average width, crack area and initial crack time (MESBAH; BUYLE-BODIN, 1999; MOON; WEISS, 2006; TOPÇU; BILIR, 2010; ZOU; WEISS, 2014). In addition, the test is very simple and does not require an extensive work, making it more attractive to be employed in a regular quality control process or qualitative evaluation of fibers available.

Within this context, the purpose of the present investigation is to evaluate the potential of fibers to reduce early age cracking caused by restrained shrinkage in rendering mortars. The ring test method was selected for this evaluation, considering all of its advantages and mainly the number of variables associated to the study with a quite large number of specimens tested simultaneously. The polypropylene fiber used in this study is recommended by producers for the application in rendering mortars. Also, this fiber presents characteristics (dimensional and mechanical) similar to those indicated in the literature for shrinkage cracking reduction (SANJUAN; MORAGUES, 1997; ALY; SANJAYAN; COLLINS, 2008; PEREIRA-DE-OLIVEIRA; CASTRO-GOMES; NEPOMUCENO, 2012). A previous study with this fiber (MONTE, BARROS, FIGUEIREDO, 2012) indicated the content of 0.3% as an upper limit to not cause adherence problems in application as render, and the use of the same fiber would complement the evaluation. The methodology presented in this study can be useful for future studies or technical evaluations of other types of fibers for use in rendering mortars.

Experimental program

Materials and mixes

The cement used for all mortars were commercial Brazilian Portland cement with 35% of blast furnace slag (CPII-E 32 cement type according to Brazilian standards). This cement was selected in order to be representative of the practical conditions of rendering mortar applications in São Paulo. A river sand with fineness modulus of 2.2 was used as an aggregate, and the granulometric distribution are presented in Figure 1.

Two rendering mortar composition were produced:

(a) ML: cement, hydrated lime (not hydraulic) and sand – representative of mortars typically mixed just before use in São Paulo construction sites. The mix proportion was adjusted in a previous study based on a job site evaluation performed using the same materials (MONTE; BARROS; FIGUEIREDO, 2012); and

(b) MC: cement, sand and air-entraining admixture (HOSTABUR OSB®). According to the fabricator information, the admixture is based on long-chain olefin sulphonate, anionic, pH 10-11 and solid content 90%. The admixture dosage was

determined by cement weight. This composition intends to be similar to dry-packaged mortars. Commercial dry-packaged mortars were not used because their material characteristics and proportions are usually not given by producers.

The physical and mechanical properties of the polypropylene fiber used in this investigation were measured following the procedure described in Motta, Agopyan and John (2007). The results of these characterizations are given in Table 1. A summary of the mixes design and their codes are presented in Table 2.

The admixture content was selected to achieve air content around 20%. The water/dry materials were calculated to the mortars with higher content of fiber (MC-0.3 and ML-0.3). The amount of water was determinate to obtain a ball penetration of 11 ± 1 mm (in dropping ball test according to the British standard). This penetration was considered suitable to mold the rings. In order to evaluate a range of fiber contents, the values 0.1, 0.2 and 0.3% in volume were selected. These contents were previously tested in rendering panels and a significant decrease could not be observed in the adhesive strengths (MONTE; BARROS; FIGUEIREDO, 2012).
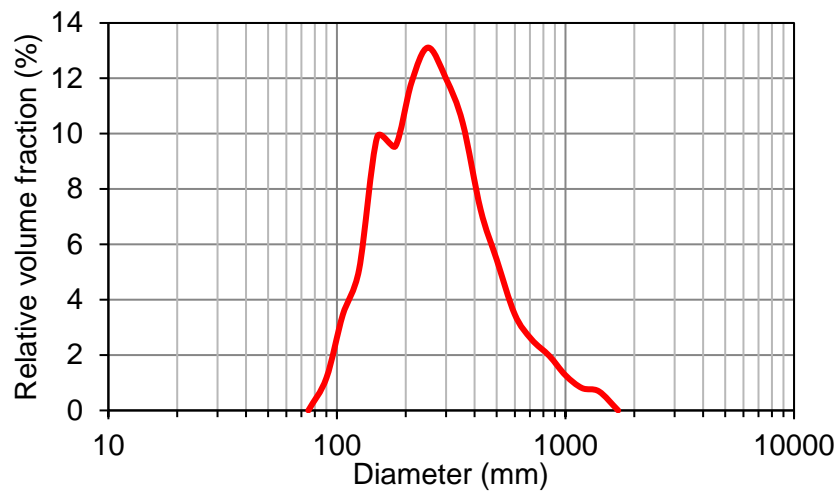
Figure 1 - Sand granulometric curve

Table 1 - Physical and mechanical properties of polypropylene fiber

Statistical parameters	Specific density (g/cm³)	Length (mm)	Diameter (µm)	Tensile strength (MPa)	Elastic modulus (GPa)
Average	0.907	6.1	15	727	4.7
Standard Deviation	0.006	0.1	1	199	0.9
Variation (%)	0.6	2	6	27	19

Table 2 - Mixes design

Mortar Code	Cement (kg)	Lime (kg)	Sand (kg)	Admixture (%)[1]	Water/dry materials (%)[2]	Fiber consumption	
						% in volume	g/m³
MC-0	1	-	5.4	0.008	15	0	0
MC-0.1	1	-	5.4	0.008	15	0.1	1000
MC-0.2	1	-	5.4	0.008	15	0.2	2000
MC-0.3	1	-	5.4	0.008	15	0.3	3000
ML-0	1	0.45	8.2	-	19	0	0
ML-0.1	1	0.45	8.2	-	19	0.1	1000
ML-0.2	1	0.45	8.2	-	19	0.2	2000
ML-0.3	1	0.45	8.2	-	19	0.3	3000

Note: [1]% of the cement weight; and
[2]% of dry materials weight.

The mortars were mixed in a 60-liter mortar mix that has four paddles around the horizontal axis, rotating at 140 ± 5 rpm. To enhance fiber dispersion, the fibers were mixed with sand and 1/3 of the water for 180 seconds. After, the previous mixture was mixed with cement, admixture and the remaining water forming MC mortars or cement, lime and remaining water forming ML mortars. The total mixing time was 270s (Figure 2).

Test methods

The bulk density of mortars in fresh state was measured to determine the mixes' air content, according to NBR 13278 (ABNT, 2005a). For the characterization of the mortars' consistency the dropping ball method was used according to British standard BS 4551 (BRITISH…, 1998). The flow table test was not used because of its limitation in mortars with high air contents (CAVANI; ANTUNES; JOHN, 1997).

The hardened characteristics were evaluated in prismatic specimens with dimensions of 40 × 40 × 160 mm according to NBR 13279 (ABNT, 2005b). The specimens were cast and placed in a dry chamber at 23 ± 2 °C and 50 ± 4% RH (relative humidity). For each mortar composition twelve specimens were molded and three specimens were evaluated in flexural tests at the ages of 3, 7, 14 and 28 days. Before the flexural tests, the specimens were evaluated with a PUNDIT® 6 Ultrasonic device with a 150 kHz transducer to determine the dynamic elastic modulus according to NBR 15630 (ABNT, 2008).

Crack measurements: Ring Test

For each mortar composition, four specimens with 25 mm in thickness and 70 mm in height were cast around a rigid steel ring with 305 mm inner diameter, totaling 16 specimens. After casting, the specimens were maintained covered with a plastic film and 24 hours later the external mold was removed. The specimen top was sealed with paraffin for the drying to occur only in the lateral face (Figure 3a). These specimens were also placed in a dry chamber at 23 ± 2 °C and 50 ± 4% RH (Figure 3b). In order to evaluate the development of visible cracking, the specimens were monitored twice a day for 21 days after casting. The time required for the first crack to appear was recorded (Figure 3c). Crack widths were monitored and measured using a crack detection microscope ELE International with magnification of 40x and accuracy of 0.02 mm (Figure 3d).

Results and discussion

Table 3 presents the results of the bulk density and the air content of the mortars studied. Furthermore, it shows the percentages of the increase of air in the mixture considering the fiber content calculated with respect to the mixture without fibers.

The results show that the air content in the mortars mixture increases with the fiber content, independently of the type of mortar. This probably happens because the addition of fibers changes the mortar rheology and prevents the air from escaping. A recent study using 0.2% of 6 mm PVA fiber shows that fiber addition can significantly increases the required mixing energy to achieve more homogeneous mortars (FRANÇA; CARDOSO; PILEGGI, 2016). This is less significant in MC mortar, which has already higher air content, presenting a maximum of 20% increase in air content when fibers are added. ML mortars shown an increase of 300% in air content when 0.3% of fibers are added, although the air content in ML mortars is low if compared to MC. Also, the correlation between air content and fiber addition, plotted in Figure 4, present similar a pattern for both mortars.

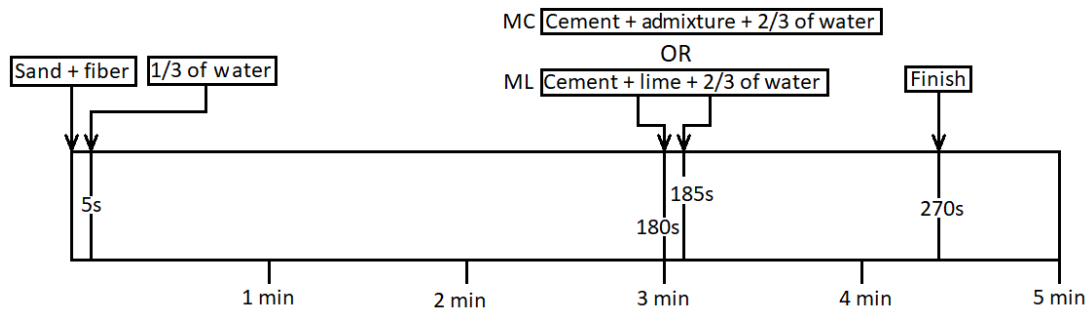Figure 2 - **Detail of the mixing routine**

Figure 3 – **(a) Top sealed ring specimen; (b) Rings stored in dry chamber; (c) Identified crack; and (d) Crack detection microscope**
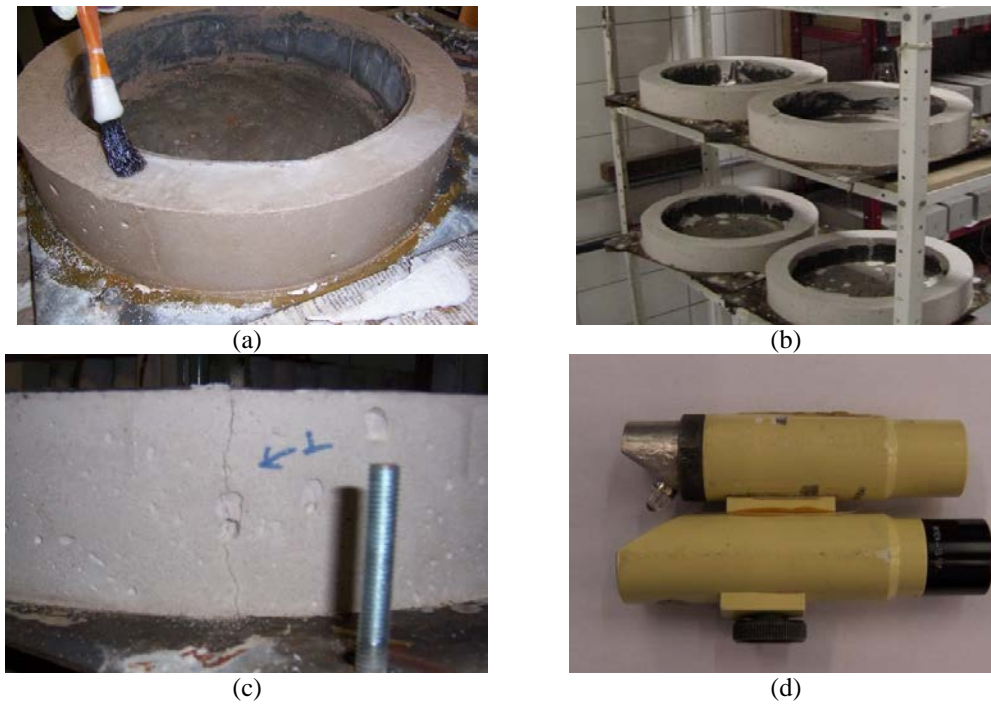

(a)

(b)

(c)

(d)

Table 3 - **Bulk density and air content of the fresh rendering mortars**

Mortar code	Bulk density (kg/m³)	Air content (%)	% increase in air content
MC-0	1720	22.2	-
MC-0.1	1680	24.0	8
MC-0.2	1660	24.8	12
MC-0.3	1620	26.6	20
ML-0	2070	1.8	-
ML-0.1	2000	4.6	156
ML-0.2	1970	6.0	233
ML-0.3	1940	7.3	306

Figure 4 - **Relationships of the dropping ball penetration and air content with the increase in fiber content**
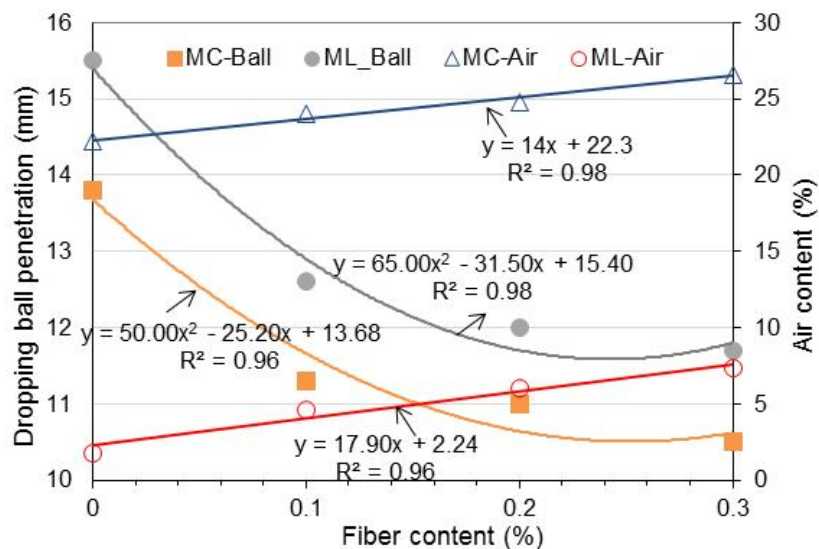
Figure 4 also shows the relationship between the results of the consistency and fiber content. The difference of the two types of mortars remained constant around 1 mm for all fiber contents. It indicates that the influence of the fiber addition in the mortars rheology was independent of the mortar composition. A reduction of the ball penetration is observed by increasing the quantity of fibers, which indicates enhanced mortar consistency. The increase in mortars and concretes consistency associated to the use up to 0.5% of short (< 20 mm) polypropylene and PVA fibers was also detected in other studies (ALY; SANJAYAN; COLLINS, 2008; PEREIRA-DE-OLIVEIRA; CASTRO-GOMES; NEPOMUCENO, 2012; FRANÇA; CARDOSO; PILEGGI, 2016). For render, the mortar rheology may have significantly influence on the tensile bond strength (STOLZ *et al.*, 2016). However, interactions with other parameters, such as substrate texture (roughness and porosity) and energy of application, lead to a more complex system that mortar rheology alone cannot explain (ZANELATTO *et al.*, 2013).

In general, the strength development over time occurred at a higher rate up to seven days, independently whether fibers had been used or not. Comparing the type of mortars, the flexural strength is higher for MC than for ML mortars. These results can be associated to higher cement content and lower water/dry materials ratio used in MC mortars. Considering the interaction fiber-matrix better results can be identified in MC mortars, including an increase in flexural strength for 0.1% of fiber. Several studies show that matrices with high mechanical strength provide a better fiber adherence, improving the composite mechanical properties (NAAMAN; NAJM, 1991; JOHNSTON, 2001; MAIDA *et al.*, 2015). Another study indicated that cement-lime mortars present worse mechanical behavior than cement mortars with the increase in fiber content (OLIVEIRA; GLEIZE; ROMAN, 2003). However, after 7 days the distance between the reference ML and those with fibers addition decrease. This may suggest that the more the mechanical strength of the matrix develops with age the better is the interaction with the fiber.

The development of flexural tensile strength of both mortars (MC and ML) is shown in Figure 5.

Figure 6 shows the evolution of the elastic modulus with age for all studied mortars.

Regarding the results of the dynamic modulus of elasticity, an increase of the fiber content leads to a reduction of the elastic modulus, independently of the type of mortar. It can be explained by the increase in air content which results in lower stiffened material (MONTE; SILVA; FIGUEIREDO, 2007). Moreover, the gain in modulus of elasticity of ML mortars takes place up to 7 days and then it remains constant. On the other hand, MC mortars present gain in modulus up to three days and then they present a slight decrease from three days to 28 days. It may be associated to the existence of water in the mortars' porosity at early ages, causing interference with the ultrasonic velocity measurement. These mortars (MC) have a higher amount of cement, which generates a less porous, and, consequently, less stiff and resistant structure than the ones observed in in ML mortars. These phenomena can influence their cracking behavior, as will be shown as follows.

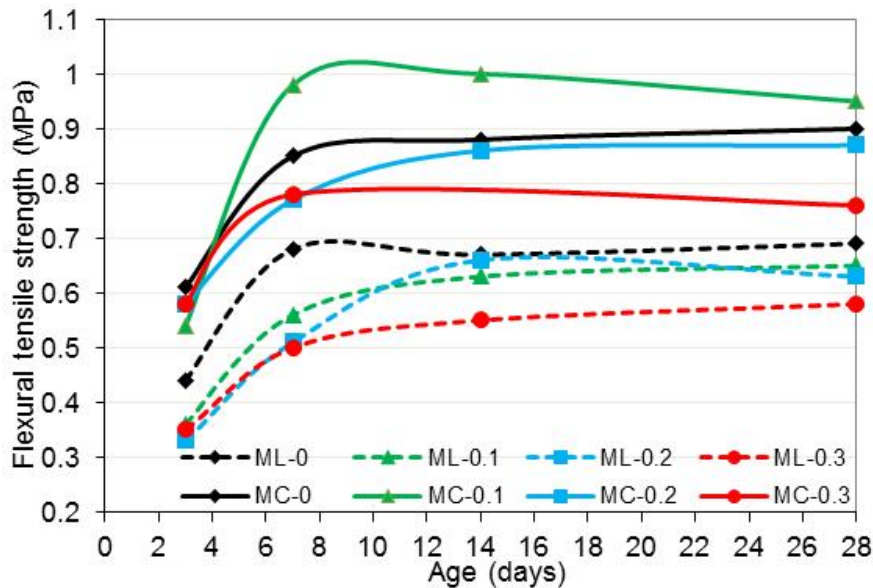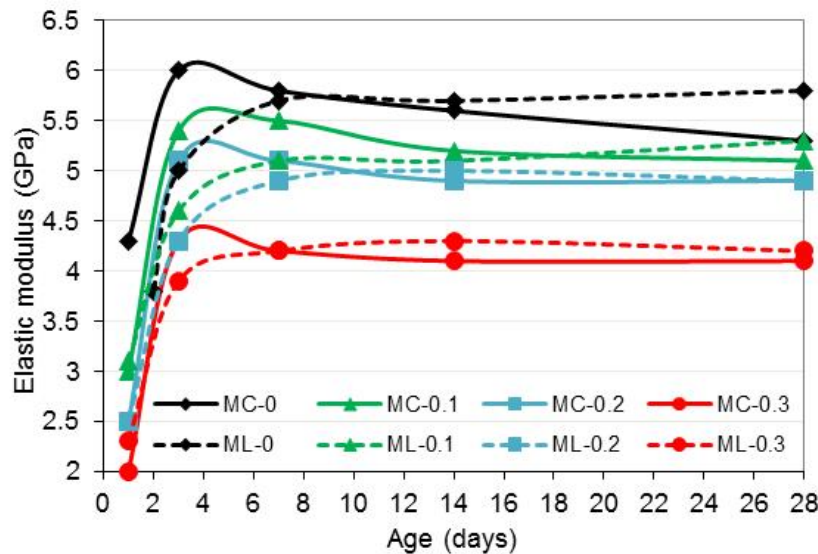Figure 5 - **Evolution of flexural strength for MC and ML mortars with age**

Figure 6 - **Evolution of elastic modulus for MC and ML mortars with mortars age**

The evolution of total crack width with age for the MC and ML mortars are shown in Figure 7 and 8, respectively, considering all the four rings produced for each mortar. Apart from this, Table 4 presents the synthesis of the cracking results from the ring tests.

The results show that the mixes without fibers present the first crack at an age of four days, independently of the mortar. In turn, the mixes with fibers present cracks at ages equal to 7 and 8 days for MC and ML mortars, respectively. Therefore, the results demonstrate that the incorporation of fibers leads to a smaller value of total crack width and a delay of the first crack, for both types of mortars. The same behavior was also documented in other studies focused on the use of polypropylene fibers (WANG; LI; BACKER, 1999; MESBAH; BUYLE-BODIN, 1999; TOLÊDO FILHO; SANJUAN, 1999). The higher crack width obtained in MC mortar without fibers must be associated to their higher stiffness at the cracking age (Figure 6). When 0.1% of fiber was added in MC, the mechanical strength improves (Figure 5) and the elastic modulus present a slightly decrease (Figure 6), resulting an expressive drop in cracking area. For higher fiber contents, the reduction in total crack width was not proportional. For ML mortar, no improvement occurs in mechanical strength with fiber addition (Figure 5). Therefore, the crack reduction was poorer for a fiber content of 0.1%. However, for 0.2% and 0.3% rate contents, the cracking was practically eliminated. In this situation, the increase in fiber content was sufficient to redistribute the stress and control the cracking. These results were compared to other studies (Figure 9) that, even though focused on more strength mortars, used polypropylene fibers in the same contents (0.1, 0.2 and 0.3%) aiming to reduce early age cracking (QI; WEISS; OLEK, 2003; BANTHIA; GUPTA, 2006).

Figure 9 shows that even with different fiber lengths the behavior of cementitious matrices follows a linear trend of cracking reduction with the increase in fiber content. The lines show a certain behavior pattern and, even beginning at different crack levels, the results show similar capacity for crack control. It is important to comment that both studies (QI; WEISS; OLEK, 2003; BANTHIA; GUPTA, 2006) did not use the ring test. In these studies, the restraint was generated by the substrate and the specimens were placed in a chamber in which hot air was blown. Nevertheless, the results obtained with the ring test show similar trend comparing with these studies that performed more complex tests.

In order to explain the mortars crack width (dependent variable) as function of some independent variables, a multiple regression was used. First, some independent variables were selected and a correlation matrix was generated (Table 5).

The correlation matrix indicated two variables (fiber content and elastic modulus) that present a Pearson correlation higher than 0.8 with the mortars crack width. Consequently, these two variables were selected to determine a multiple regression Equation 1:

Crack width $= -4.44 \times$ *Fiber content* $+ 0.3012 \times$ *Elastic modulus*   Eq. 1

This equation yields a coefficient of determination (R^2) equal to 0.924, representing that the variables in the regression model explain more than 90% of the crack width variability. Besides this, a

coefficient R²pred equal to 0.864 was observed, which reflects how well the model predicts future data. Table 6 presents the results of the analysis of variance (ANOVA) performed using a MINITAB® 17 statistical software.

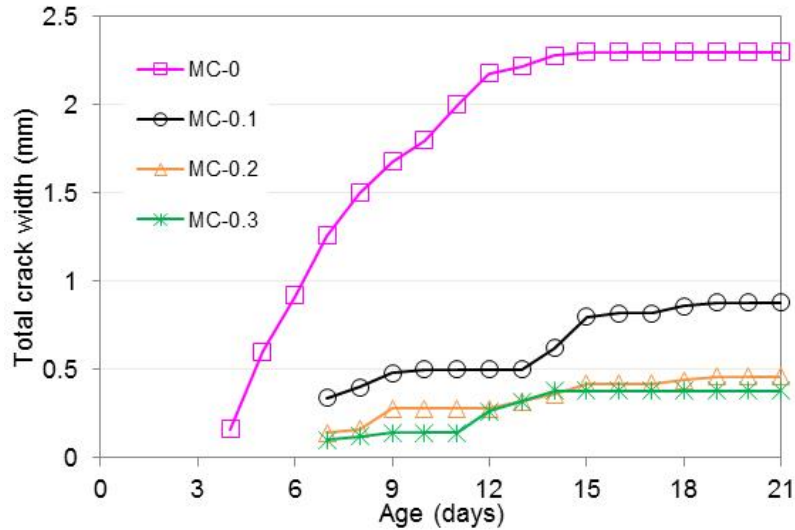Figure 7 - **Evolution of total crack width with age for the MC mortars used in the study**

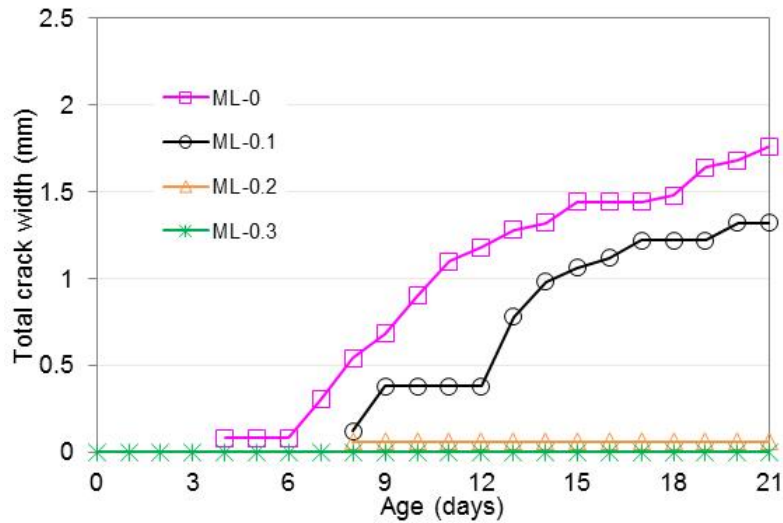Figure 8 - **Evolution of total crack width with age for the ML mortars used in the study**

Table 4 - **Synthesis of the cracking measurements results**

Mortar Code	Fiber volume (%)	Time of first crack (days)	Total crack width (mm)	Crack area (mm²)	% reduction in crack area
MC-0	0	4	2.06	166	0
MC-0.1	0.1	7	0.88	62	63
MC-0.2	0.2	7	0.46	32	81
MC-0.3	0.3	7	0.38	27	84
ML-0	0	4	1.76	128	0
ML-0.1	0.1	7	1.32	95	26
ML-0.2	0.2	8	0.06	6	95
ML-0.3	0.3	0	0	0	100

Figure 9 - **Comparison of crack area reduction with fiber content**
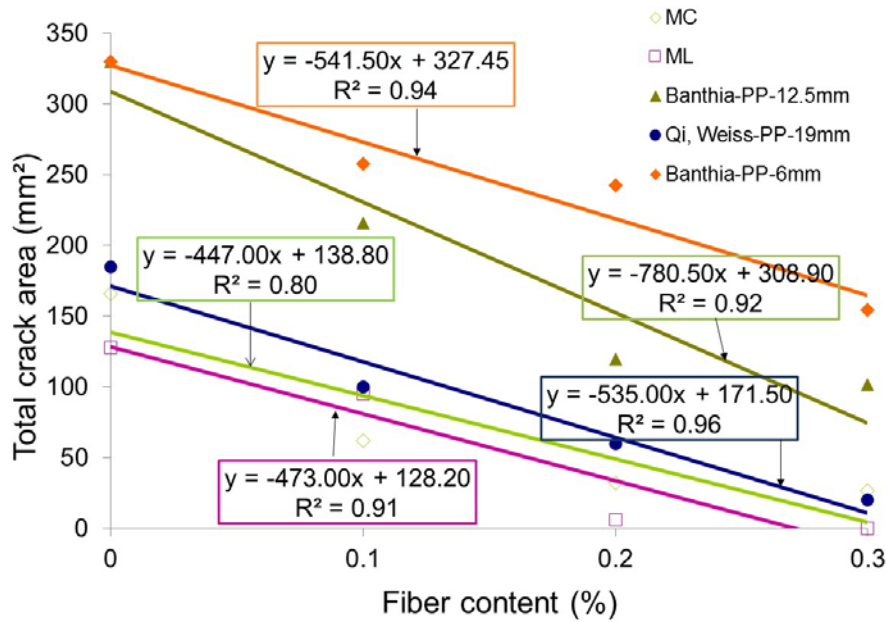
Table 5 - **Correlation matrix of the variables**

Crack width	1							
Fiber content	**-0.922**	1						
Air content	-0.061	0.180	1					
Water/Dry mat	-0.110	0.000	-0.983	1				
Cem-lime/Dry mat	0.110	0.000	0.983	-1.000	1			
Cement/Dry mat	0.110	0.000	0.983	-1.000	1.000	1		
Elastic modulus	**0.821**	-0.960	-0.024	-0.152	0.152	0.152	1	
Flexural strength	0.300	-0.267	0.810	-0.876	0.876	0.876	0.401	1

Table 6 - **Multiple regressions for crack width: Analysis of Variance**

Source	DF	SS	MS	F-value	P-value
Regression	2	9.4369	4.71844	36.26	0.000
Fiber content	1	2.5616	2.56158	19.69	0.004
Elastic modulus	1	8.7517	8.75173	67.26	0.000
Error	6	0.7807	0.13012		
Total	8	10.2176			

The analysis of variance table shows the amount of variation in the response data explained by the predictors and the amount of variation left unexplained. The p-values are the most important results to be considered. Considering a significance level (α) equal to 0.05, the p-value obtained for the Regression equal to 0.000 indicates that the regression coefficients are significantly different from zero. In addition, both parameters evaluated were significant (p-value = 0.004 for fiber content and p-value = 0.000 for elastic modulus).

Figure 10 shows a plot of the crack width determined experimentally versus the values predicted by the model.

A high correlation between experimental and predicted data was obtained (R^2 equal to 0.980). The model indicates that crack width decreases with fiber content (coefficient -4.44), as expected. Furthermore, the crack width increases as the mortar stiffness increases (coefficient + 0.3012).

Figure 10 - **Plot of measured versus predicted crack width**
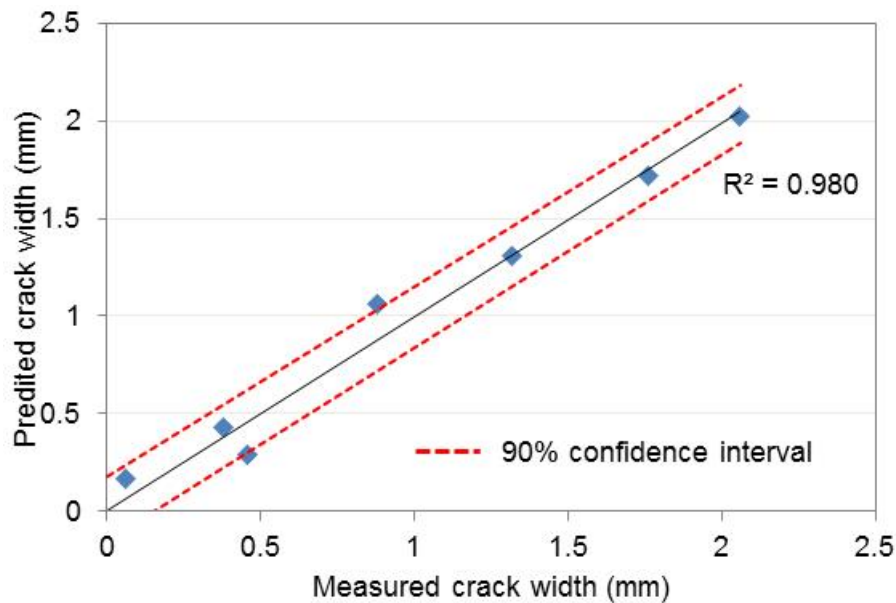
Conclusions

The following conclusions are drawn from the findings of this study:

(a) by increasing the amount of fibers, the mixes present higher values of both the consistency and content of air. The consistency increase due to the fibers' addition significantly increases the required mixing energy to achieve more homogeneous material, whereas the air content is higher because of the difficulty in removing the air introduced during the mixing process;

(b) regarding the mechanical properties evaluated in this study, the addition of fibers in the mixes does not cause an important improvement. Instead, ML mixes with the incorporation of fibers presented lower results than the ones without fibers. However, the study limited to measure the tensile strength, without the evaluation of residual strength that fibers are proven to be more efficient. Furthermore, in rendering mortars, a high mechanical strength does not ensure performance;

(c) the use of polypropylene fibers leads to a smaller value of total crack width and a delay of the first crack. In addition, the study showed that the elastic modulus has a higher correlation with the mortars crack width. Both parameters were successfully used to predict the mortars' crack width and further studies can be developed to improve this model;

(d) the ring test method may be a suitable test method to evaluate the capacity of the polypropylene fiber to control the crack formation in mortars subjected to restrained shrinkage. The

results observed using the ring test were similar to the ones performed by Qi, Weiss, Olek (2003) and Banthia, Gupta (2006). In these studies, the restraint was generated by the substrate (plate or slabs) and a chamber in which hot air was blown was used in order to intensify the cracking process. In the case of ring test, the mortar is casted around a restraining core and is allowed to shrink against it. The results demonstrated that it is sufficient to induce a cracking pattern and successfully evaluated the fibers' contribution in rendering mortars.

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