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Analysis of the influence of chlorides on the mechanical behaviour of HPSFRCC

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Abstract

High-performance steel fibre reinforced cementitious composites (HPSFRCC) present optimized mechanical properties. Due to the large amount of randomly distributed steel fibres in the cementitious matrix, the composite aesthetic aspect and mechanical response may be damaged in elements subject to chloride exposure. The objective of this research is to evaluate the mechanical behaviour of uncracked HPSFRCC specimens subjected to chloride exposure. Eight mixes of HPSFRCCs with different fibre contents (40, 80, 120 and 160 kg/m^3) and with the addition of chlorides were designed. Mechanical properties of the composites were evaluated by 3-point bending tests and the presence of corrosion products in the specimen cross-section was analysed by visual inspection. Results showed that the chloride added to the mixes has little influence on the post-cracking response of the composite.

Análise da influência de cloretos no comportamento mecânico de compósitos cimentícios de alto desempenho reforçados com fibras de aço

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Resumo

Compósitos cimentícios de alto desempenho reforçados com fibra de aço (HPSFRCC) apresentam propriedades mecânicas otimizadas. Devido à grande quantidade de fibras de aço distribuídas aleatoriamente na matriz cimentícia, o aspecto estético do compósito e a resposta mecânica podem ser prejudicados em elementos sujeitos à exposição a cloretos. O objetivo deste trabalho é avaliar o comportamento mecânico de corpos de prova de HPSFRCC não fissurados submetidos à exposição a cloreto. Foram produzidas oito misturas de HPSFRCCs com diferentes teores de fibra (40, 80, 120 e 160 kg/m^3) e com adição de cloretos. As propriedades mecânicas dos compósitos foram avaliadas por ensaio de flexão de 3 pontos e a presença de produtos de corrosão na seção transversal da amostra foi analisada por inspeção visual. Os resultados mostraram que o cloreto adicionado às misturas tem pouca influência na resposta pós-fissuração dos compósitos.

Análisis de la influencia de los cloruros en el comportamiento mecánico de compósitos cementícios de alto desempeño reforzados con fibras de acero

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Resumen

Compósitos cementícios de alto desempeño reforzados con fibra de acero (HPSFRCC) tienen propiedades mecánicas optimizadas. Debido a la gran cantidad de fibras de acero distribuidas aleatoriamente en la matriz cementícia, el aspecto estético del compósito y la respuesta mecánica pueden verse perjudicados en elementos sujetos a exposición a cloruros. El objetivo de este trabajo es evaluar el comportamiento mecánico de muestras de HPSFRCC no fisuradas sometidas a exposición a cloruro. Se produjeron ocho mezclas de HPSFRCC con diferentes contenidos de fibra (40, 80, 120 y 160 kg/m^3) y con la adición de cloruros. Las propiedades mecánicas de los materiales compósitos se evaluaron mediante el ensayo de flexión de 3 puntos y la presencia de productos de corrosión en la sección transversal de la probeta se analizó mediante inspección visual. Los resultados mostraron que el cloruro agregado a las mezclas tiene poca influencia en la respuesta post-fisuración de los compósitos.

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1. Introduction

Steel fibre reinforced concrete (SFRC) is a composite with optimized post-crack behaviour provided by the addition of fibres in the brittle cementitious matrix. For structural applications, high-modulus fibres can be used to substitute, partially or totally, conventional reinforcement (DI PRISCO; PLIZZARI; VANDEWALLE, 2009). Several researchers have highlighted the improvement of mechanical behaviour in SFRC structural properties and applications (ALVAREZ, 2013; DI PRISCO, 2009; NAAMAN, 2004; RIZZUTI; BENCARDINO, 2014; THOMAS; RAMASWAMY, 2007).

Steel fibre in uncracked specimens presents a superior resistance to corrosion compared to conventional rebar due to the smaller dimensions of the fibre that favours the fibre-matrix interface (BERROCAL; LUNDGREN; LÖFGREN, 2016; DAUBERSCHMIDT, 2006; FRAZÃO et al., 2016; NORDSTRÖM, 2005; SADEGHI-POUYA et al., 2013). Moreover, chloride threshold concentrations need to be higher to oxidize steel fibres than to oxidize steel rebars (DAUBERSCHMIDT, 2006). Studies in SFRC subjected to chloride exposure have reported corrosion limited to steel fibres up to 5 mm from the surface. Regarding accelerated chloride corrosion in high-performance steel fibre reinforced concrete (HPSFRC), only minor surface corrosion is observed (BALOUCH; FORTH; GRANJU, 2010; GRANJU; BALOUCH, 2005; SERNA; ARANGO, 2008).

Due to the minor corrosion, the effect of chloride exposure in uncracked SFRC samples leads to a negligible influence on the mechanical performance of the composite (ALIZADE; JANDAGHI ALAEE; ZABIHI, 2016). No changes on the post-crack behaviour of corroded uncracked SFRC compared to no-corroded specimens were observed after wet-dry cycles in the study of Graff et al (2009). However, the research conducted by Mantegazza and Gatti (2004) highlighted a reduction in the mechanical performance, while Kim, Boyd and Lee (2011) indicated a slight increment in the mechanical behaviour of SFRC under chloride cycles.

Specimens of HPSFRC subjected to various corrosive environments (salt ponding, immersion in 3% and 10% of chloride solution) presented no reduction in the mechanical properties after long-term test (ABBAS, 2014). Such result was attributed to the dense microstructure and strong bond among aggregates, cementitious materials and steel fibres in the matrix. By contrast, SFRC specimens subjected to a corrosive environment (immersed in a 3.5% NaCl solution) showed a slight loss of flexural strength and toughness according to Carrillo, Pulido and Aperador (2017). These works demonstrate that the effects of chlorides on the mechanical post-crack behaviour of fibres in HPSFRCs are still unclear.

In this context, this work aims to assess the effects of corrosion on the mechanical response of uncracked HPSFRCCs specimens subjected to an accelerated chloride exposure. An experimental programme was conducted with eight mixes of HPSFRCCs produced with four different fibre contents (40, 80, 120 and 160 kg/m^3) and with the addition of chloride to the mixes. The 3-point test and the visual inspection of the cross-section were performed at different ages. Results showed a small reduction on the post-crack behaviour of the composite the presence of oxidized fibres on the cross-section of the specimen, close to its surface.

2. Experimental methodology

2.1. Materials and mixes

The experimental methodology presenting the materials, mixes, specimen preparation and curing conditions for the experimental programme is described in detailed in a previous paper from the research group (VIEIRA; CAVALARO; AGUADO, 2021). Table 1 shows the composition of the 8 mixes designed for the experimental programme.

In total, 36 specimens measuring 40 mm x 40 mm x 160 mm (height x width x length) were produced per mix. Mixes with no chloride are identified by 'F_fibre content' and mixes containing chloride are identified by 'F_fibre content - Cl'.

2.2. 3-point bending test

3-point bending tests were performed according

Table 1. Properties of fibres used (provided by the manufacturer).

Components	F_40	F_80	F_120	F_160	F_40 - Cl	F_80 - Cl	F_120 - Cl	F_160 - Cl
CEM I 42.5 R (kg/m^3)	700	700	700	700	700	700	700	700
Limestone filler (kg/m^3)	255	255	255	255	255	255	255	255
Sand (0/2 mm) (kg/m^3)	631.6	623	608.6	594.3	631.6	623	608.6	594.3
Sand (0/5 mm) (kg/m^3)	340.1	335.4	327.7	320	340.1	335.4	327.7	320
Water (kg/m^3)	213.5	213.6	210.9	208.2	213.5	213.6	210.9	208.2
Superplasticizer (kg/m^3)	31.5	31.5	35	38.5	31.5	31.5	35	38.5
Retarder (kg/m^3)	2.1	2.1	2.1	2.1	2.1	2.1	2.1	2.1
Steel fibre (kg/m^3)	40	80	120	160	40	80	120	160
Sodium chloride (kg/m^3)	-	-	-	-	44	44	44	44
Flow diameter (mm)	209	213	215	210	209	210	211	209

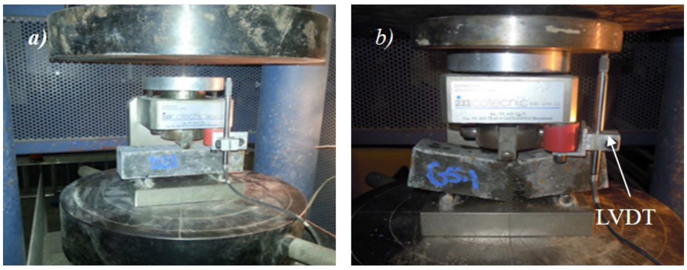

Fig. 1. 3-point bending test: (a) specimen in the apparatus for the test and (b) specimen failure after the test.

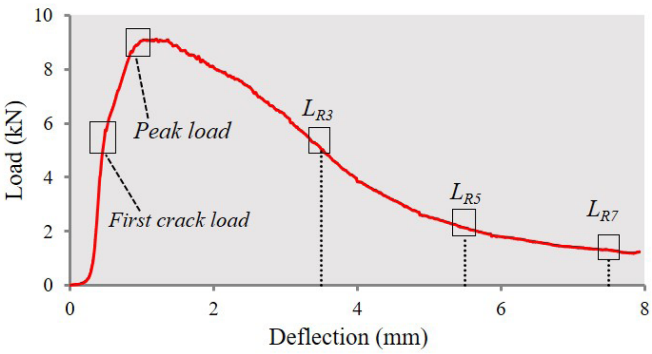

Fig. 2. Parameters derived from the load-deflection curves.

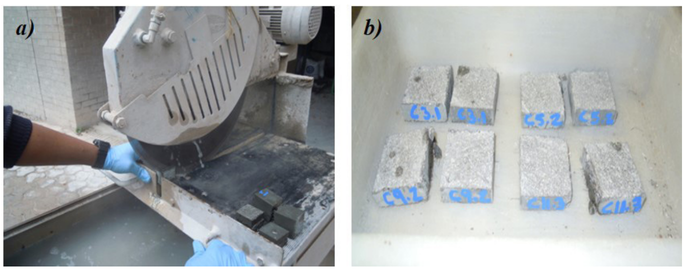

Fig. 3. Specimen preparation: (a) cutting of the 1-cm thick slices and (b) 2 pieces of each specimen for the inspection.

to UNE-EN 196-1 (AENOR, 2005). An Ibertest MEH 3000 kN press and a bending apparatus were used. The vertical displacement of the press was monitored by a LVDT to control the load application rate (Figure 1). For each age and mix, 4 specimens were tested at 16, 30, 49 and 109 days after casting.

Figure 2 presents the main parameters from the bending test, which are the first crack load, the peak load and the residual loads L_{R3}, L_{R5} and L_{R7} (at a distance of 3, 5 and 7 mm from the first crack deflection, respectively). Corrosion was analysed considering the presence of chlorides, age, curing condition and fibre content.

2.3. Visual inspection of the cross-section

After the bending tests, 2 slices (10 mm thick) were cut from each specimen perpendicular to the cross-section of the specimen (Figure 3). After cleaning, the cross-sections of the specimens were analysed with a Stereo Microscope to identify fibre corrosion spots.

3. Results and discussion

3.1. 3-point bending test

3.1.1. Load-deflection curves

Figure 4 presents the average load-deflection curves of specimens with and without chlorides for all mixes and ages. A general overview reveals that the shape of the curves of mixes with chloride is similar to that found in specimens with nochloride. Although chlorides may affect cement hydration and cause corrosion, they did not affect the shape of the curves.

Until the first crack appears, the elastic response of the composite is observed, which is governed by

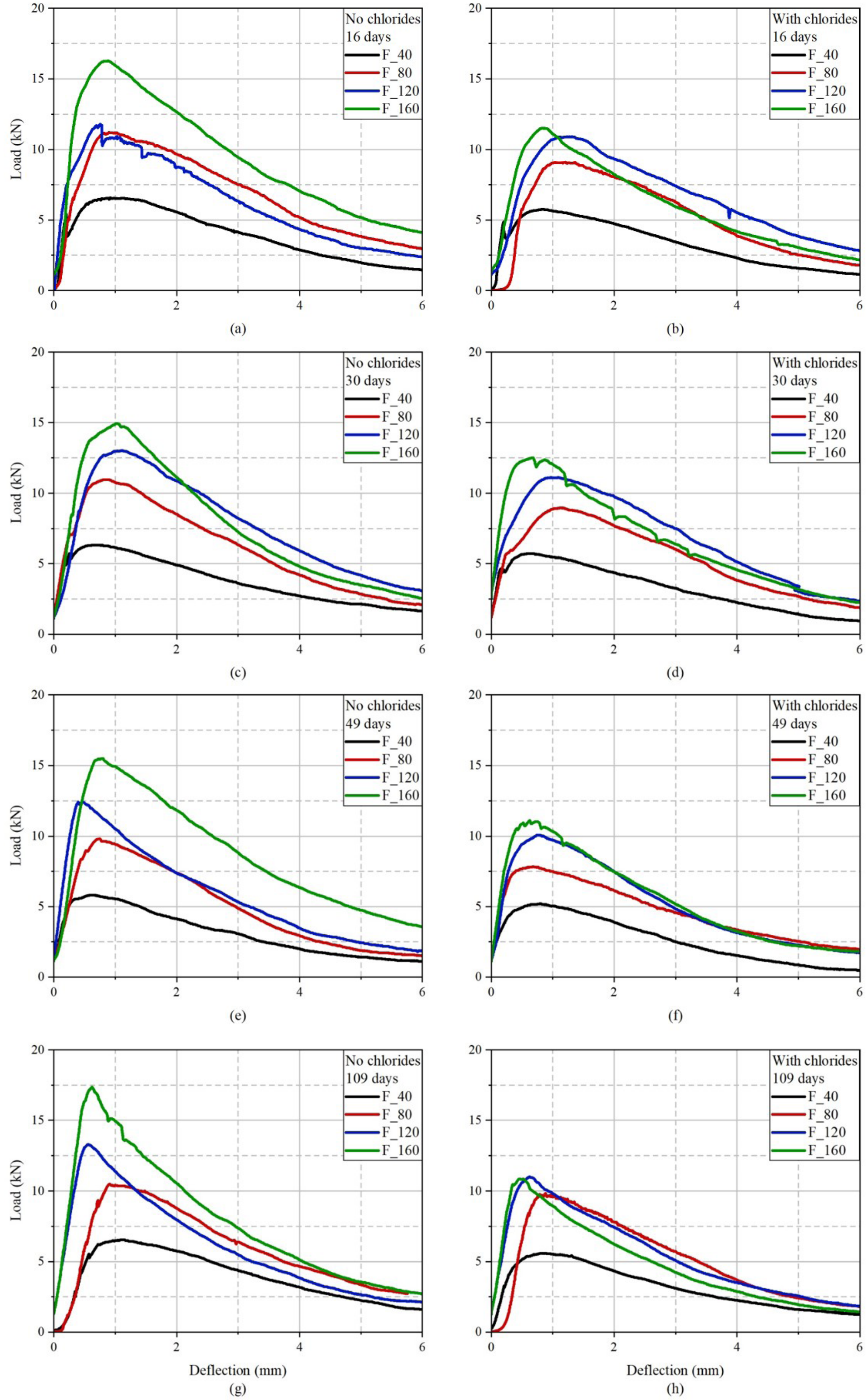

Fig. 4. Average load-deflection curves of specimens from mixes F_40, F_80, F_120 and F_160, tested at different ages.

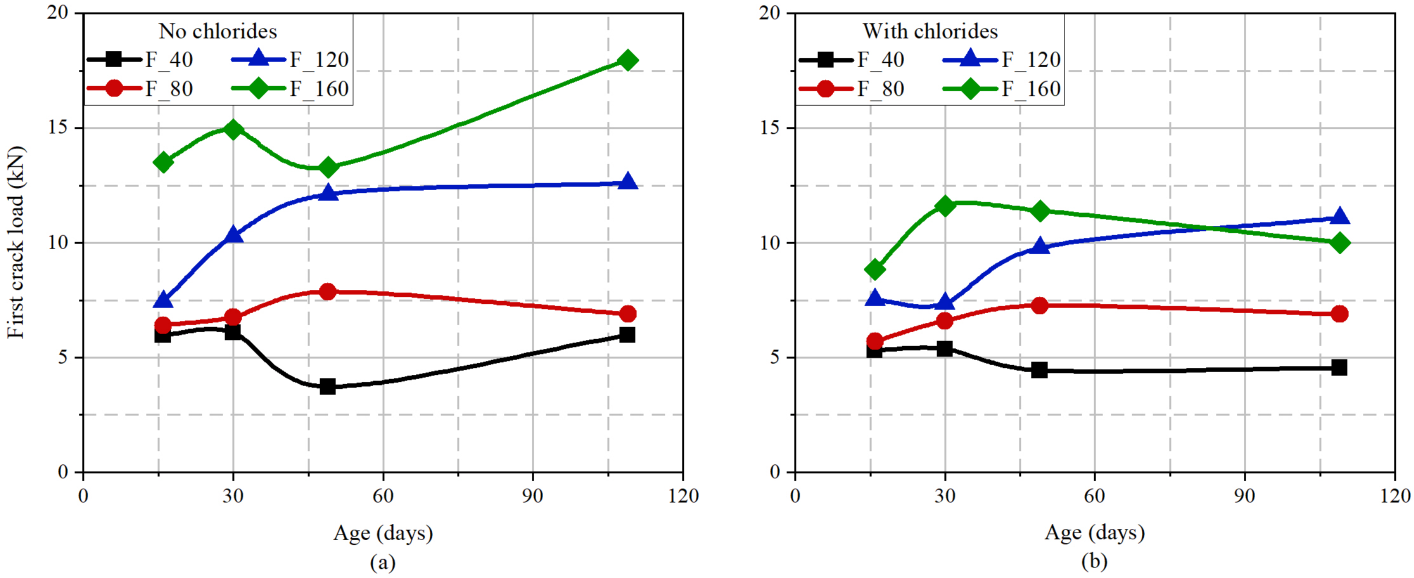

Fig. 5. First crack load of specimens from mixes F_40 F_80, F_120 and F_160: (a) specimens without chlorides and (b) specimens with chlorides.

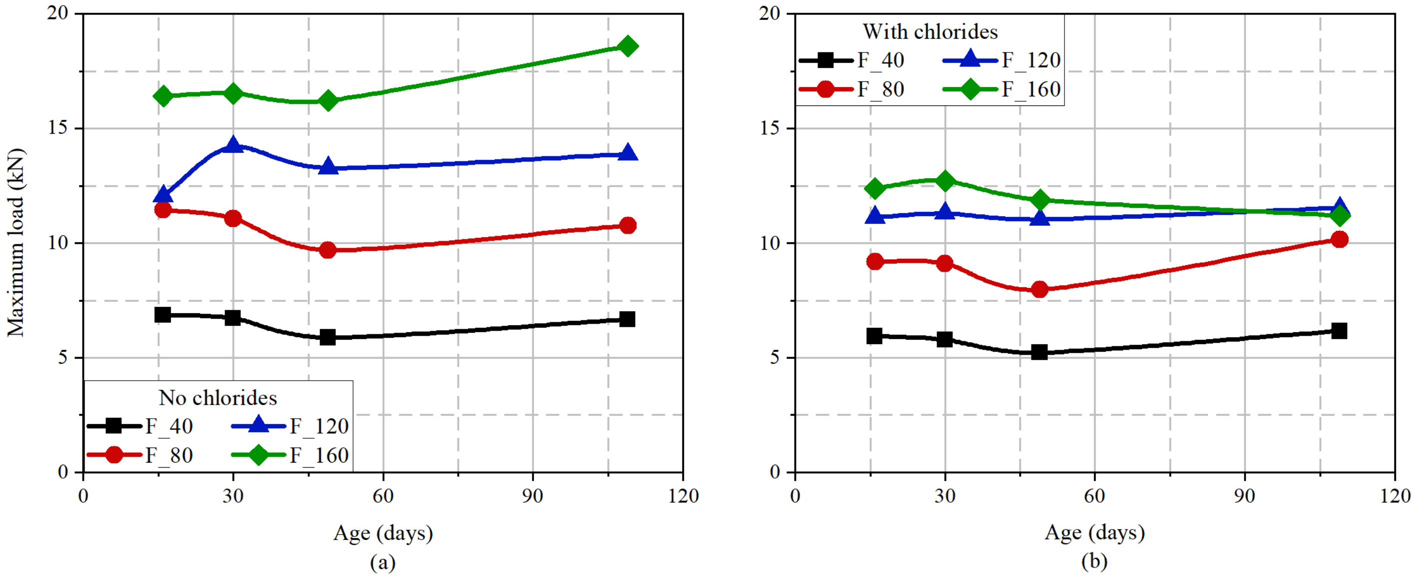

Fig. 6. Maximum load of specimens from mixes F_40 F_80, F_120 and F_160: (a) specimens without chlorides and (b) specimens with chlorides.

the matrix properties with a limited contribution of the fibres. After that, an increase of both load and displacement is observed as the load is transferred to fibres, which bridge multiple cracks, leading to a deflection-hardening behaviour. Once the peak load is reached, the localization of cracks takes place, leading to a reduction of the load-bearing capacity of the specimen.

3.1.2. First crack

Figure 5 shows the first crack load measured at 16, 30, 49 and 109 days for mixes F_40, F_80, F_120 and F_160 with and with no chlorides. The use of chlorides reduces the load bearing capacity of the matrix. Specimens with no chlorides present slightly higher values of first crack load in comparison with equivalent specimens with chlorides. This may be a consequence of the change in cement hydration induced by the chlorides (TAYLOR, 1997). No clear trend on how the difference varies with the age, curing condition or fibre content is observed.

3.1.3. Maximum load

Figure 6 shows the average maximum load values of specimens from mixes F_40 F_80, F_120 and F_160 with and without chlorides at the ages of at 16, 30, 49 and 109 days. The maximum load is reached after multiple crack formation. At this stage, the main mechanism contributng to the load-bearing capacity of the specimen is the fibre-matrix

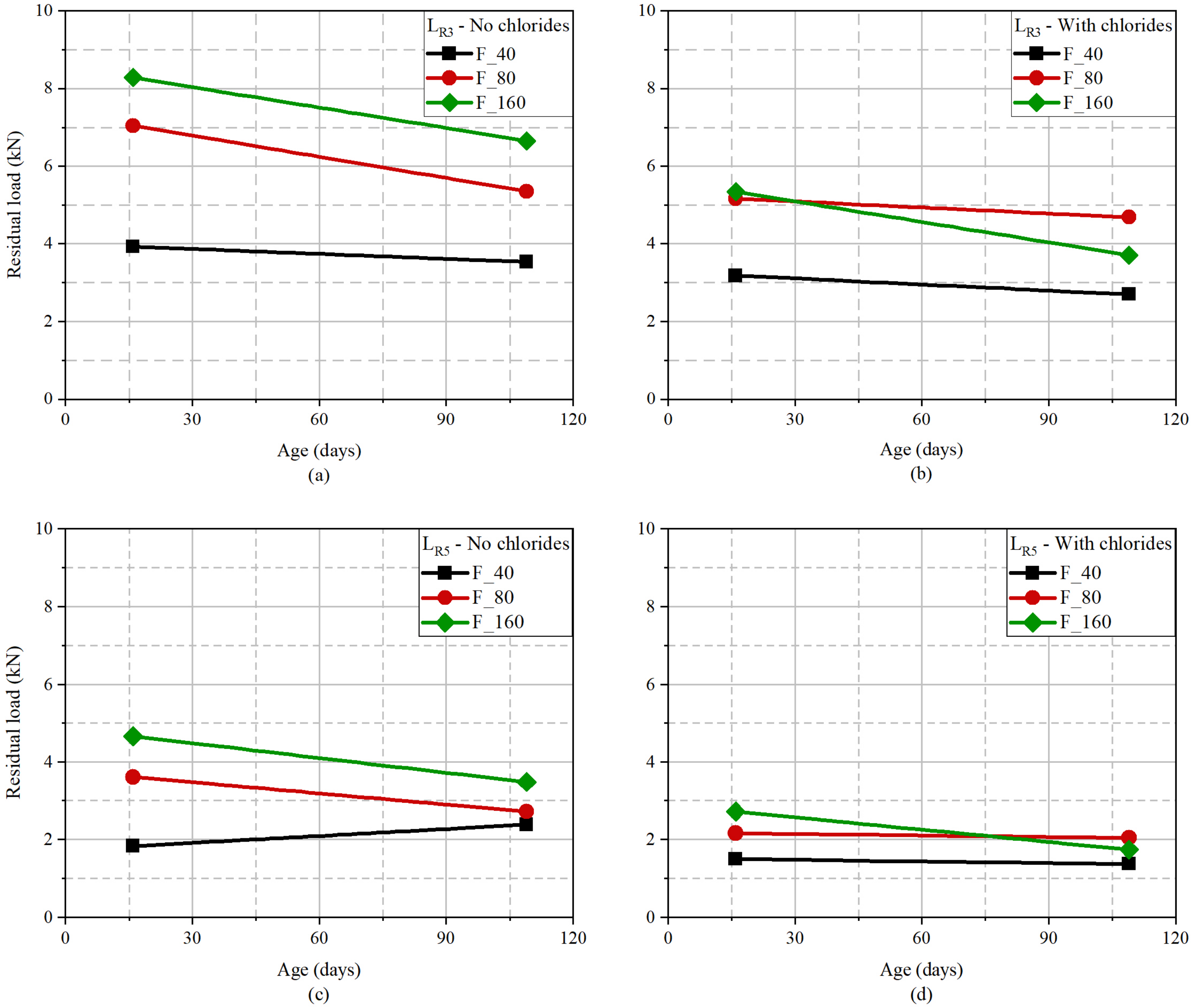

Fig. 7. Residual load of specimens from mixes F_40 F_80 and F_160: (a) and (c) specimens without chlorides and (b) and (d) specimens with chlorides.

bond. Chloride addition leads to a reduction of the load-bearing capacity of the composite due to its influence on cement hydration and fibre oxidation.

Considering fibre corrosion as the main cause for the reduction on the load-bearing capacity of specimens, more significant reductions would be observed over time, increasing the difference between the maximum load obtained in mixes with and without chloride. This contradicts results from Figure 6, suggesting that the main cause of the difference in the maximum load is the influence of chlorides on cement hydration. Since no reduction in the maximum load was observed over time, fibre corrosion was not detrimental. The dense matrix due (low w/c and high cement content) limits ion diffusion needed to activate corrosion.

3.1.4. Residual load

Figure 7 shows the residual loads L_{R3} and L_{R5} of specimens from mixes F_40 F_80 and F_160 with and without chlorides at the ages of at 16 and 109 days. L_{R3} and L_{R5} are observed after the peak-load, indicating a progressive crack opening characterized by fibre pullout.

Residual load values decrease over time, whereas the difference between specimens with and without chlorides increases with time. Such trend is more evident in mixes with higher fibre content. This suggests a possible influence of the corrosion process in the results, although definitive conclusions may not be drawn due to the influence of the chlorides in the hydration process.

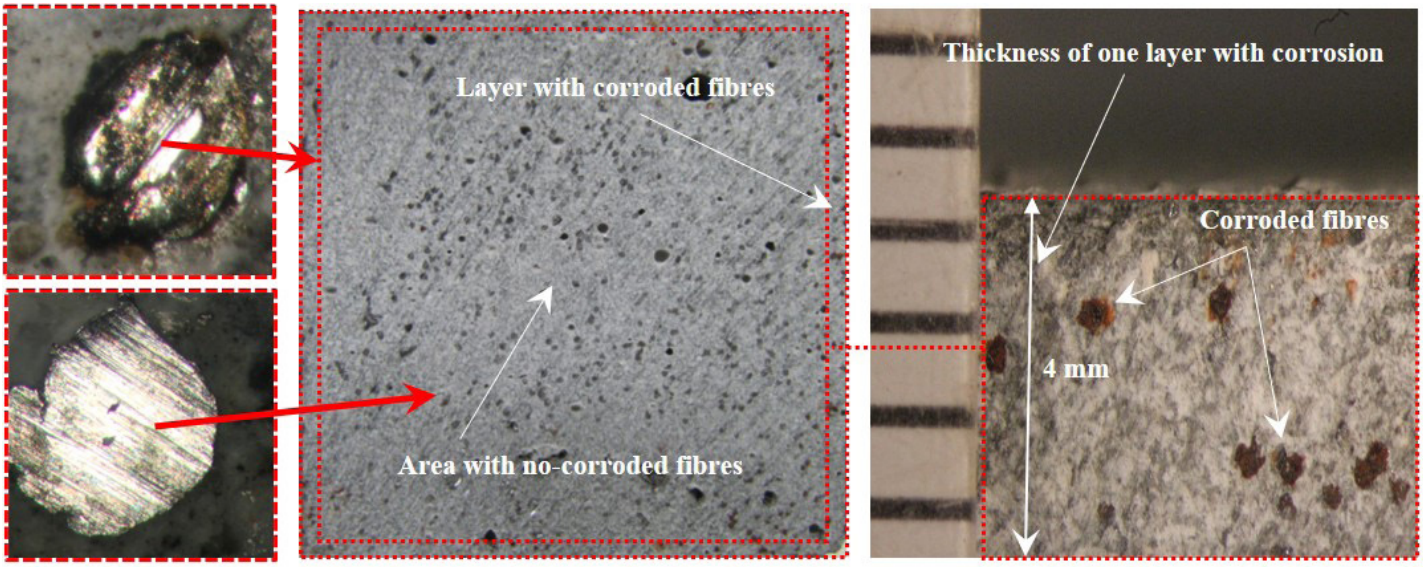

Fig. 8. Cross section of one specimen with chlorides.

3.2. Analysis of fibres at the specimen cross-section

Specimens were visually inspected immediately after the bending tests. Figure 8 shows the cross-section of a specimen with chlorides, indicating that only fibres close to specimen surface presented signs of corrosion. On the contrary, fibres in the interior region of specimen showed no sign of corrosion. Such result was expected because the high density of the matrix does not allow water and oxygen penetration in the specimen. Therefore, only a very superficial corrosion was observed. No corrosion occurred in specimens with no chlorides.

4. Conclusions

- A decrease in the first crack load and maximum load values were observed in specimens from mixes containing chlorides. The difference between the load of specimens with and without chloride remains constant over time. The most probable cause is the influence of chlorides on the cement hydration process.

- A decrease is also observed in the residual load, whose reduction becomes more evident over time. The influence of fibre corrosion may not be discarded and additional studies are necessary for a proper explanation of this process.

- The visual inspections of specimens after the 3-point bending tests confirm that corrosion occurred only in fibres located close to the surface. Most of the cross-section showed no signs of corrosion, despite the high chloride content. This confirms that the low diffusion coefficient of the matrix limits the availability of oxygen and water required to activate the corrosion, thus protecting the fibres.

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