Comportamiento a flexion del hormigón armado con barras de acero y fibras de polipropileno en condiciones variables de carga y fisuración sometido a la penetración de cloruros

Flexural performance of reinforced concrete with steel rebar and polypropylene fibres under various loading and cracking conditions subjected to chloride ingress

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RESUMEN

En este artículo se presentan los resultados de un estudio experimental sobre la corrosión inducida por cloruros en vigas de hormigón con barras de refuerzo y fibras de polipropileno. Las vigas se dividieron en dos grupos: uno expuesto a una solución de cloruro al 3% durante tres meses y otro no expuesto (referencia). Cada grupo incluía vigas no pre-fisuradas y pre-fisuradas (0,20 y 0,30 mm de ancho de fisura) bajo cargas sostenidas. La corrosión en las vigas pre-fisuradas comenzó a los siete días, mientras que las vigas no pre-fisuradas permanecieron pasivas. Las vigas pre-fisuradas mostraron una reducción del 23-28% de la capacidad de carga y del 49-52% de la ductilidad en comparación con las vigas de referencia. El comportamiento estructural de las vigas no pre-fisuradas no mostró cambios significativos.

ABSTRACT

This paper reports findings from an experimental study on chloride-induced corrosion in concrete beams reinforced with steel rebar and polypropylene fibres. Beams were divided into two groups: one exposed to a 3% chloride solution for three months and another unexposed (reference). Each group included uncracked (non-loaded) and pre-cracked beams (0.20 and 0.30 mm crack widths) under sustained loads in three-point bending setup. Corrosion in cracked beams began within seven days, whereas uncracked beams remained passive over the three-month period. Cracked beams exhibited a 23–28% reduction in load-bearing capacity and a 49–52% reduction in ductility compared with reference beams. Structural performance of uncracked beams showed no significant changes.

PALABRAS CLAVE: corrosión, cloruro, hormigón, barras de refuerzo, fibras, polipropileno
KEYWORDS: corrosion, chloride, concrete, rebar, fibre, polypropylene, fibre reinforced concrete

1. Introduction

Chloride induced corrosion of steel is a complex electrochemical process that results in the reduction of resistant cross-section of the reinforcing bars and deposits of corrosion products (rust), leading to an increase of stresses in the material. In several instances [1] [2] corrosion was identified as contributing factor to the structural collapse. Importance of devising strategies to mitigate corrosion damage was further recognized by he National Association of Corrosion Engineers (NACE) from United States. In their report [3] it was estimated that 3.4% of the global gross domestic product (GDP) or 2.5 trillion $ is spent on direct maintenance costs associated with corrosion damage in infrastructure, with indirect costs estimated to be 10 times higher.

Cracks have been recognized to be an important parameter with regards to the durability of reinforced concrete (RC). Namely, if other important parameters are equal (such as concrete quality, water to cement ratio, concrete cover) shorter initiation time of corrosion is observed in cracked elements compared with those uncracked. Therefore, contemporary design codes such are ACI 318 [4] or EC2 [5] prescribe limiting values of crack widths as a mean to assure proper durability of RC elements.

In recent decades, an innovative concept of using fibres as a means of controlling cracking in concrete has been investigated. Results show that the addition of fibres is effective in arresting crack growth and altering the cracking pattern [6] with more closely spaced and narrower cracks in fibre reinforced concrete (FRC) [7] [8].

Improved water tightness of cracked elements containing fibres was observed in the literature review by Berrocal et al. [9], thus implying enhanced durability. Similarly, Paul et al. [10] directly correlated improved post-cracking behaviour of FRC to the reduced penetration of chlorides through the concrete matrix. Improvements in structural performance of RC elements where fibres were used as additional reinforcement were also observed.

Leporace-Guimil et al. [11] investigated the performance of cracked tension ties under simultaneous exposure to chlorides and sustained axial tensile loads. Their study compared steel rebar- and steel fibre-reinforced concrete (RR-SFRC) and conventional RC elements. The authors observed a larger reduction of ultimate strain, 26% for RC and 22% for RR-SFRC elements. Reduction of tensile capacity was observed to be 6% for both type of elements.

Bafghi et al. [12] studied structural performance of uncracked and elements with flexural cracks not subjected to sustained load. The authors observed higher reduction of load-bearing capacity in cracked RC elements (22% to 30%) compared with cracked RR-SFRC which even showed a slight increase compared with reference elements (5% to 16%).

Differences in structural performance between RC and steel rebar- and macro synthetic fibre-reinforced concrete (RR-MSFRC) were studied by Blunt et al. [13]. The authors observed a greater loss of load bearing capacity in RR-MSFRC than in RC elements (9% and 3%, respectively) compared with their uncorroded counterparts. However, despite the greater relative loss, in absolute terms, corroded RR-MSFRC elements still resisted 28% higher ultimate loads than corroded RC ones.

Berrocal et al. [14] investigated the structural performance of elements exposed to chlorides under various loading and cracking conditions. The authors observed lower loss of rotational capacity in RR-MSFRC and RR-SFRC elements compared to RC. Furthermore, elements that were kept under sustained or cyclical loads performed worse than non-loaded or unloaded ones. Faster corrosion initiation was observed in cracked elements compared with uncracked ones.

The reviewed studies indicate reduced mechanical degradation in corroding elements when fibres are combined with traditional steel rebar. However, varying experimental parameters (e.g., loading, cracking, environmental conditions, exposure duration, concrete properties) complicate direct comparisons. Hence, a study with the goal of comparing the flexural performance of traditional RC elements to those having fibres in combination with steel rebar was devised so that only fibre type, loading, and cracking conditions are variables. This paper presents results of the devised experimental campaign relating to elements where polypropylene fibres are used in combination with steel rebar.

2. Experimental program

Concrete beams (150 × 150 × 600 mm) were reinforced with a single 6 mm diameter B500B bar, classified as normal ductility rebar according to EC2 [5]. In order to avoid influencing fibre orientation with mechanically induced vibrations, self-compacting concrete (SCC) with a water-to-cement ratio (w/c) of 0.46 was used in element production. For the production of 1 m^3 of concrete, the following materials were used: 475 kg of cement, 230 kg of water, two fine aggregate fractions (0/2 mm and 0/4 mm) and two coarse aggregate fractions (4/10 mm and 10/20 mm) with 360 kg, 880 kg, 150 kg and 300 kg respectively. To improve concrete workability a plasticizer and superplasticizer admixtures were used (values expressed as % of cement mass): 0.70% and 1.73%, respectively.

A fibre volume fraction (v_f) of 0.67% (equalling to 6 kg/m^3) of polypropylene fibres was adopted in order to achieve residual flexural strength corresponding to SLS ($f_{R,1}$ according to *fib* Model Code 2010 [15]) in the range between 1.0 and 2.0 MPa.

The study considered elements with three discrete values of crack widths (w): w = 0.00 mm (uncracked) and pre-cracked elements with w = 0.20 mm and w = 0.30 mm. Elements were divided into two groups: unexposed elements (reference) and elements exposed to a 3% sodium chloride (NaCl) solution over a period of three months.

Uncracked elements were not loaded for the duration of the experimental program, whereas pre-cracked elements were kept under sustained loads in a three-point bending (3PB) configuration (Figure 1). To facilitate crack opening in the mid-section of the beams, specimens selected for pre-cracking were notched in the midpoint of the span by 25 mm.

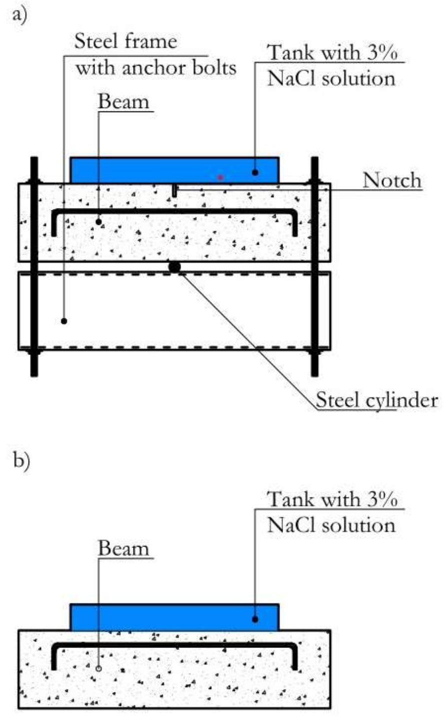

Figure 1. Beams exposed to a chloride solution a) cracked and under sustained loads b) uncracked and not loaded

After casting, all elements were kept under controlled conditions (temperature 20° C ± 2° C and relative humidity of 98%) for 28 days. Pre-cracking of the selected beams was performed in 3PB, by using the INSTRON 8505 servo hydraulic system. During the pre-cracking procedure, linear variable differential transducers (LVDTs) were installed to monitor the values of crack widths. Pre-cracked elements were mounted on steel frames, and sustained loads were generated by fastening anchor bolts and the steel cylinder placed in the midpoint of the steel frame (Figure 1). Fastening of anchor bolts was stopped once the target value of crack widths was achieved in the pre-cracked beams. Periodically, crack widths were measured and anchor bolts were adjusted if necessary to keep values of crack widths constant.

Steel rebar was installed with 25 mm of concrete cover to the surface (in case of pre-notched specimens, cover was adopted as 25 mm below the notch).

2.1 Methodology

For the duration of the experiment, corrosion current density (i_{corr}), corrosion potential (E_{corr}) and resistivity of the concrete matrix (ρ_M) were periodically measured by using the GECOR 10 [16] device (SAFECOR ingenieria Sl., Spain) to determine corrosion initiation and to monitor corrosion propagation. Multiple meassurments were taken, after which average values were used in the analysis. Successive meassurments were taken only once values of E_{corr} stabilized from previous measurements. Values were deemed valid if the ratio between maximal and minimal values did not differ by more than the factor of four [17].

Elements were kept under atmospheric conditions in the interior of the LATEM laboratory of the Universitat Politècnica de Catalunya for 90 days, with hourly meassurments of temperature (T) and relative humidity (RH). After 90 days, elements were moved to a climatic chamber with T = 20° C ± 2° C and RH = 60% ± 5%, where they were kept for 7 more days with the goal of quantifying the effects of ambient conditions.

After 97 days from exposure, all elements were subjected to failure in 3PB, using the same setup as in the pre-cracking procedure. During testing, values of midpoint displacement and applied force were recorded in order to quantify load-bearing capacity and overall structural performance. Depth of chloride penetration was determined by using the colorimetric method [18]. After failure in flexural tests, surfaces of cross-sections of the beams were sprayed with a silver nitrate solution (AgNO3) with a 0.1 mol concentration. In regions where chlorides were present, the solution reacted and coloured the surface white, whereas regions without chlorides were coloured in a light-yellow shade.

3. Results and discussion

The characterization of compressive (f_c) and tensile strength (f_{ct}), modulus of elasticity (E) and residual flexural strength ($f_{R,i}$) was performed on elements after 28 days of curing.

The following average values of mechanical properties were obtained: f_c = 45.25 MPa, f_{ct} = 3.12 MPa, E = 30.92 GPa, $f_{R,1}$ = 1.59 MPa, $f_{R,2}$ = 2.12 MPa, $f_{R,3}$ = 2.43 MPa, $f_{R,4}$ = 2.57 MPa (where values of $f_{R,1}$, $f_{R,2}$, $f_{R,3}$, and $f_{R,4}$ correspond to crack mouth opening displacement of 0.5, 1.5, 2.5 and 3.5 mm, respectively).

3.1 Non-destructive tests

Beams are named as wXX-Y-Z, where wXX is the crack width (in mm × 100), Y indicates the exposure conditions (E for exposed, NE for non-exposed), and Z is a ordinal number (e.g., w20-E-8 represents a beam with 0.20 mm crack width exposed to chlorides with ordinal number 8). Figure 2 and Figure 3 show the evolution of i_{corr} (on the primary axis) and T or RH, respectively, (on the secondary axis) over time (t). Corrosion initiation in cracked specimens (w30-E-1 and w20-E-8) was observed in 1st week based on values of i_{corr}. Results are complemented by Figure 4 where the evolution of E_{corr} over time is presented.

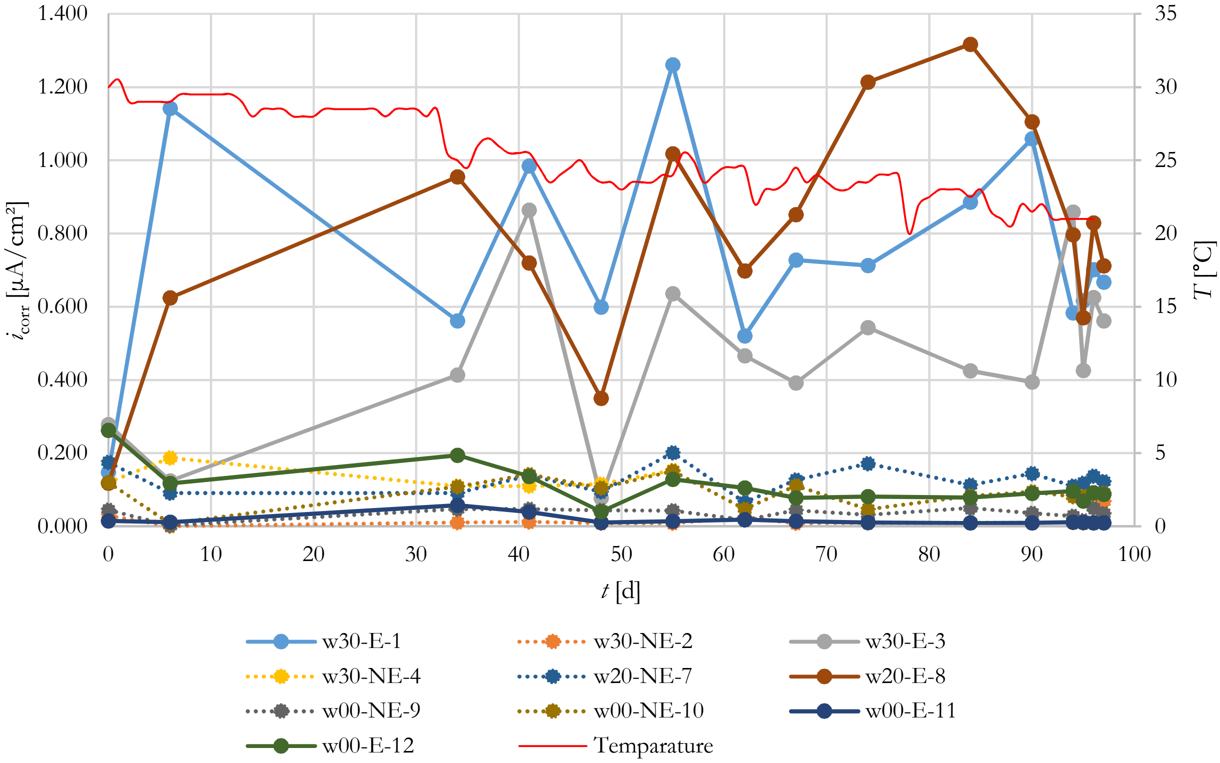

Figure 2. Evolution of i_{corr} and T over time

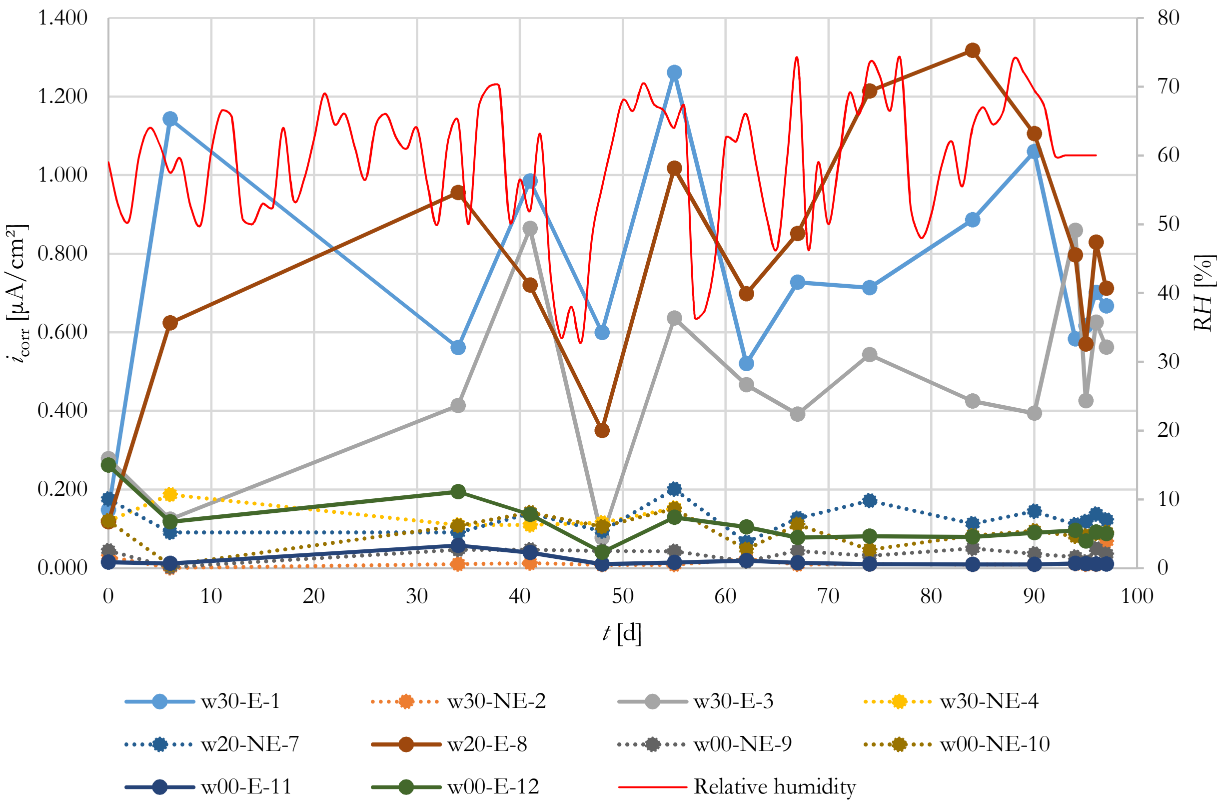

Figure 3. Evolution of i_{corr} and RH over time

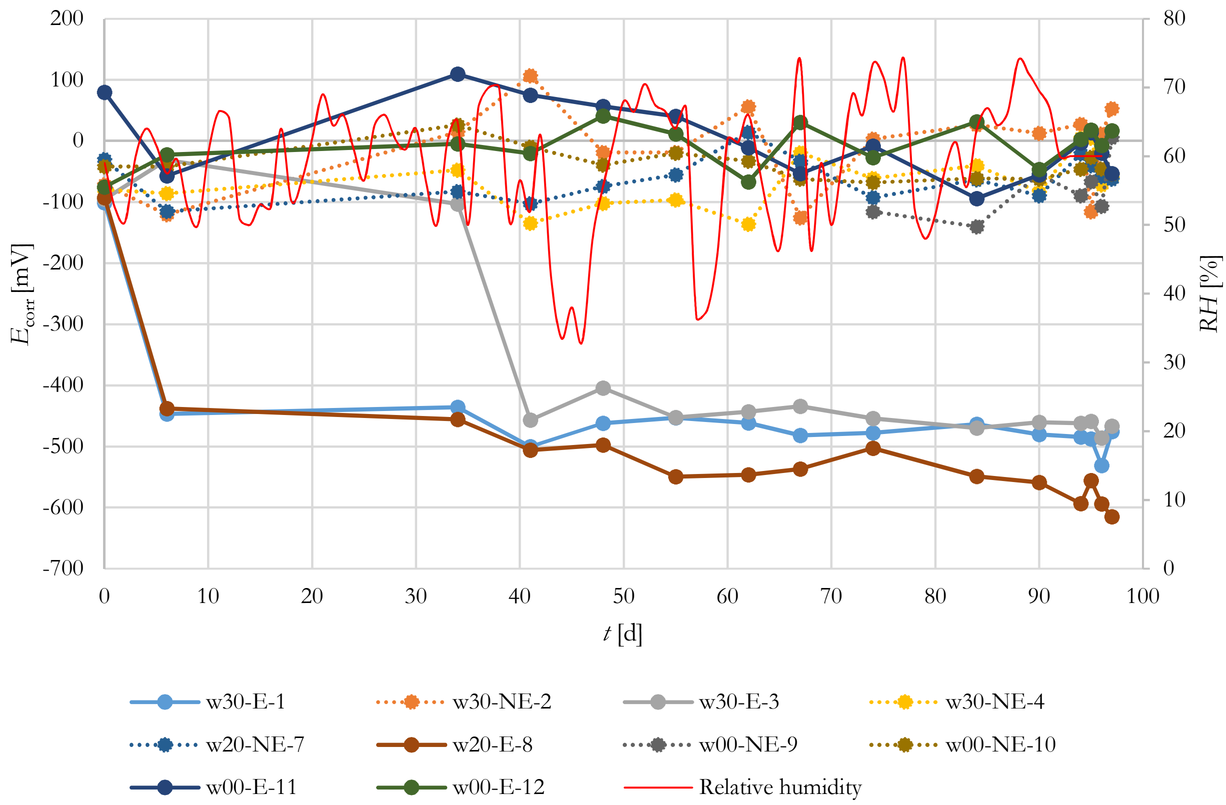

Figure 4. Evolution of E_{corr} and RH over time

One specimen (w30-E-3) remained passive until 34 days of exposure to chlorides This implies that crack width is not the only governing parameter when it comes to corrosion initiation. However, once corrosion was initiated its behaviour became more similar to other corroding elements. Significant influence of both T and RH on the measured values of i_{corr}, was observed, whereas values of E_{corr} remained less sensitive to changes in ambient conditions. In the environment with controlled ambient conditions (exposure from 90th to 97th day), elements still showed some variation with regards to the corrosion rate, although to a much smaller extent.

Those results point to beam w30-E-3 potentially being an outlier due to specific local conditions of the beam itself (e.g. exposed to more hours of direct sunlight compared with other beams) especially during the hottest days of the summer, where biggest differences in i_{corr} and E_{corr} are measured. All remaining beams (uncracked exposed, uncracked unexposed and cracked exposed) remained in the passive state for the entire duration of the campaign.

3.2 Flexural test to failure

In Figure 5, loads (P) and midpoint displacements (d) of beams loaded in flexure until failure are presented. In case of uncracked beams recorded load values were adjusted to consider differences in lever arm between uncracked and cracked elements. Namely, of rebar in cracked elements was positioned 50 mm beneath the surface in mid-section (25 mm of concrete cover plus 25 mm notch), whereas rebar in uncracked elements was positioned 25 mm below the surface (Figure 1)

All elements were observed to fail in flexure (Figure 6), however with significant differences between corroded and uncorroded elements.

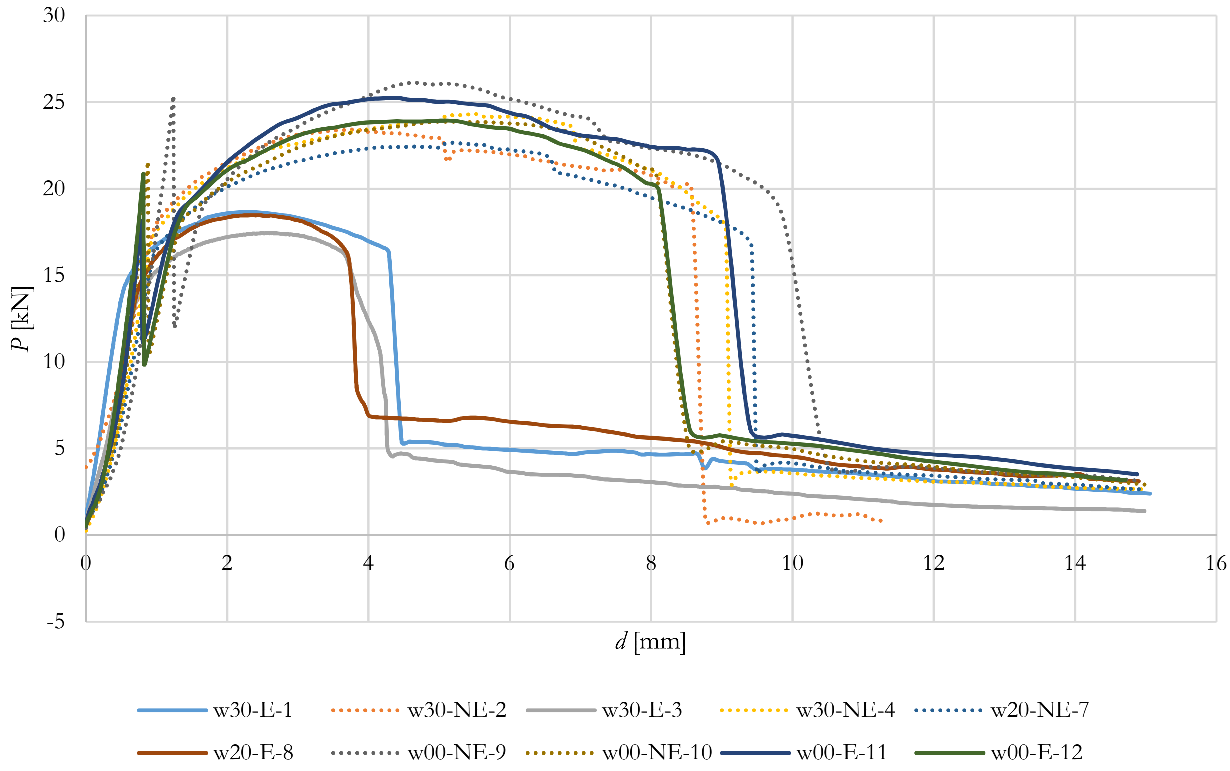

Figure 5. Load-displacement diagram in 3PB until failure

a) b)

Figure 6. Typical observed failure a) corroded beam, b) uncorroded beam

Relative to uncorroded and unexposed specimens, no significant reduction in the value of load and displacement that correspond to the onset of rebar yielding (P_y and d_y, respectively) was observed in any of the beams regardless of their exposure or cracking condition (Figure 5). When it comes to the values of maximal loads (P_{max}) and ultimate loads (P_u), similar values were observed, except in the case of pre-cracked and exposed (corroding) beams (Figure 7). In case of elements with values of w = 0.30 mm, P_{max} and P_u were reduced by 28% and 26%, respectively. Slightly lower degradation was observed in elements with w = 0.20 mm where P_{max} and P_u were reduced by 26% and 23%, respectively.

A higher degree of degradation was observed when it comes to the ductility of the corroded sections. From Figure 5, a much lower value of ultimate displacement (d_u) between corroded and uncorroded elements is evident. Expressing ductility as the ratio between d_u and d_y, an average degradation of 47% and 25% may be calculated for elements with w = 0.20 mm and w = 0.30 mm, respectively.

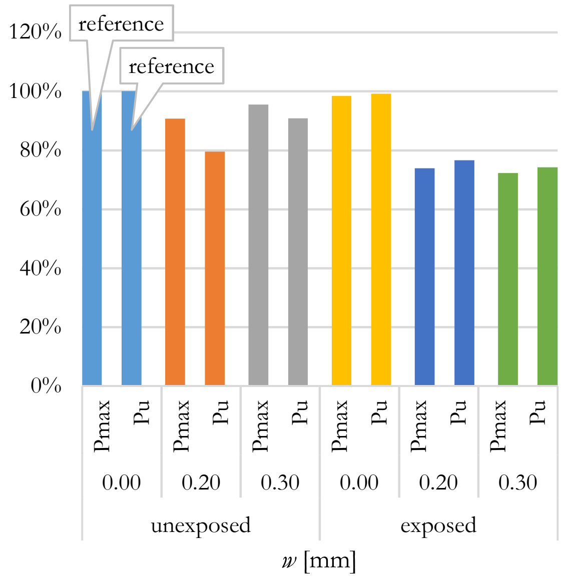

Figure 7. Comparison of structural performance relative to uncracked and unexposed beams

By integrating the area below the load-displacement curve, the degradation of both load bearing and ultimate displacement may be considered. The average loss of ductility expressed via energy (E) amounts to 52% and 49% for elements with w = 0.20 mm and w = 0.30 mm respectively.

Effects of chloride corrosion were clearly visible on the cross sections of elements after destructive tests were performed. The red-brown area in Figure 8 indicate deposits of corrosion products, whereas white parts surrounding it indicate zones where chlorides reacted with the $AgNO_3$ solutions. In Figure 9, the cross section may be observed to be clean of both corrosion products and chloride penetration, thus, this confirming that the rebar remained passive.

Figure 8. Typical cross section of a corroded beam (pre-cracked and exposed)

Figure 9. Typical cross section of an uncorroded beam (uncracked and exposed)

4. Conclusions

This contribution presents results derived from an experimental program carried out on 10 beams where polypropylene macrofibres were used in combination with steel rebar, one half of which was exposed to 3% NaCl solution, whereas the other half remained unexposed. In the study, non-destructive methods were used to detect corrosion initiation and monitor its propagation. Structural performance (in terms or load-bearing capacity and ductility) was assessed in a three-point bending test. The conducted investigation supports the following conclusions:

- Corrosion initiation was determined in the first week of exposure in pre-cracked elements, for both values of pre-crack widths (0.20 and 0.30 mm).
- All uncracked elements (exposed and unexposed) and cracked but unexposed elements remained passive for the entire duration of the experimental program.

- Relative to uncorroded and unexposed elements, only corroded beams suffered significant degradation of load bearing capacity. Reduction of P_{max} was slightly higher for elements with w = 0.30 mm than in elements with w = 0.20 mm (28% and 26% respectively). Similar trend was observed for values of $P_{u,}$ where reduction of 26% and 23% was observed for elements with w = 0.30 mm than in elements with w = 0.20 mm.
- Corrosion had a larger effect on ductility than on load-bearing capacity. Expressed in terms of energy, ductility was 52% and 49% lower (w = 0.20 mm and w = 0.30 mm, respectively) compared with uncracked and non-exposed beams.
- Based on the results of the colorimetric method, chloride penetration was observed only in the case of cracked and exposed beams.

The conclusions are based on ongoing experiments. Future results are expected to complement current findings and enhance understanding of the structural performance and durability of elements reinforced with fibres and rebar.

Acknowledgments

This research has been supported by the Ministry of Science and the Investigation (Ministerio de Ciencia e Innovación) and the State Research Agency (Agencia Estatal de Investigación) of the Kingdom of Spain. The project reference: PID2019-108978RB-C32, the grant reference: PRE2020-095457. Special acknowledgements go to Master Builders Solutions (Trotsberg, Germany) who provided generous material support of this investigation and technical stuff in LATEM laboratory of UPC.

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