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# Experimental assessment of a controlled-polarization technique for the in-situ measurement of corrosion rate in reinforced concrete.

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## ABSTRACT
This work presents the experimental evaluation of a novel methodology for the in situ assessment of corrosion in reinforced concrete structures. The technique is based on dynamic control of the applied current to maintain appropriate polarization conditions. Laboratory tests were conducted on specimens with different concrete types and exposure conditions. The results show improved polarization control compared to previous generations of confined current corrosion meters, with corrosion rate values comparable to those obtained with reference techniques such as Linear Polarization Resistance and embedded multiparametric systems. The originality lies in ensuring appropriate polarization regardless of corrosion state through a non-invasive approach, demonstrating strong potential as an effective tool for corrosion diagnosis.
**Keywords:** reinforced concrete; corrosion; non-destructive techniques; in-situ testing; durability.

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**Contribution of each author**
In this work, J.E. Ramón and I. Martínez contributed to the original idea, with a participation of 50% each. The development of the methodology was carried out by J.E. Ramón (30%), A. Castillo (20%), J.R. Lliso-Ferrando (30%) and A. Martínez-Ibernón (20%). The experimentation and data collection were mainly carried out by J.E. Ramón (80%), with the participation of A. Castillo (20%). The writing of the manuscript was carried out by J.E. Ramón (80%) and I. Martínez (20%). All authors participated in the discussion and interpretation of results and in the approval of the final version of the manuscript.



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# Evaluación experimental de una técnica con polarización controlada para la medición in situ de la velocidad de corrosión en hormigón armado.

## RESUMEN

Este trabajo presenta la evaluación experimental de una nueva metodología para la evaluación in situ de la corrosión en estructuras de hormigón armado. La técnica se basa en el control dinámico de la corriente aplicada para asegurar una polarización adecuada. Se realizaron ensayos en laboratorio con distintos tipos de hormigón y condiciones de exposición. Los resultados muestran un mejor control de la polarización respecto a generaciones anteriores de corrosímetros por corriente confinada, con valores de velocidad de corrosión comparables a técnicas de referencia como la Resistencia a la Polarización Lineal y sistemas multiparámetro embebidos. La originalidad radica en asegurar la polarización adecuada independientemente del estado de corrosión mediante una aproximación no invasiva, con potencial como herramienta eficaz de diagnóstico.

**Palabras clave**: hormigón armado; corrosión; técnicas no destructivas; inspección in situ; durabilidad.

# Avaliação experimental de uma técnica com polarização controlada para a medição in situ da taxa de corrosão em concreto armado.

## RESUMO

Este trabalho apresenta a avaliação experimental de uma nova metodologia para a avaliação in situ da corrosão em estruturas de concreto armado. A técnica baseia-se no controle dinâmico da corrente aplicada para manter condições de polarização adequadas. Ensaios laboratoriais foram realizados com diferentes tipos de concreto e condições de exposição. Os resultados mostram um melhor controle da polarização em relação a gerações anteriores de corrosímetros por corrente confinada, com valores de taxa de corrosão comparáveis aos obtidos por técnicas de referência, como a Resistência à Polarização Linear e sistemas multiparamétricos embutidos. A originalidade reside em assegurar a polarização adequada independentemente do estado de corrosão por meio de uma abordagem não invasiva, demonstrando elevado potencial como ferramenta eficaz de diagnóstico da corrosão.

**Palavras-chave:** concreto armado; corrosão; técnicas não destrutivas; inspeção in situ; durabilidade.

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# 1. INTRODUCTION

The corrosion of rebars is one of the main pathologies to affect reinforced concrete structures (RCSs) and it compromises their durability and service life (Sun et al., 2010). It is essential to monitor for this phenomenon to prevent damage and optimise maintenance costs. To this end, various non-destructive techniques (NDTs) have been developed over the years, most notably, the in-situ measurement of corrosion rate ($V_{CORR}$), expressed as current density ($i_{CORR}$), which can be used to estimate the service life by means of models published in the Spanish Structural Code (Ministerio de Fomento, 2021) or Eurocode 2 (CEN, 2005).

While technological advances have been achieved with respect to new constructions (Duffó and Farina, 2009; Alcañiz et al., 2016; Ramón, 2018), there are still only limited solutions available focussing specifically on existing structures. Among the most popular systems for testing established structures are those based on a confined galvanostatic current (CGC), although they have operational limitations. A recent study of over 1800 field measurements (Ramón et al., 2021) reported a high error rate due to polarisation outside the appropriate range (effective polarisation ≈ 5–30 mV)[1], which compromised the reliability of $V_{CORR}$ measurements made using a linear polarisation resistance method.

In this context, the research team behind the study developed and patented a new method that focused on dynamic control of the applied current to overcome the above limitations (Martínez and Ramón, 2021). Within the framework of the SMART (PID2020-119744RB-C22) and SEGHOSENS (CPP2023-010657) projects, the method was implemented using portable equipment designed for the in-situ testing of corrosion in RCSs. The system can be used to measure the concrete's corrosion rate ($V_{CORR}$), corrosion potential and resistivity. Here we present the first experimental assessment of the method's performance compared to standard techniques with a view to determine if it is a feasible diagnostic tool for field applications.

# 2. PROCEDURE

This study analyses some of the first results of corrosion measurements obtained using a patented, dynamically controlled, confined current method (hereinafter, DYN method) (Martínez and Ramón, 2021). The method was implemented within a portable device designed for in-situ testing of the state of corrosion in reinforced concrete elements. In this study, we used the same electrode configuration in the portable probe as that described in the patent.

The main innovation in our method compared to the one originally developed by Feliu et al. (Feliu et al., 1992), which was designed around a confined galvanostatic current from a guard ring (hereinafter, EST method), was the incorporation of an automated polarisation current control protocol. This means the rebar polarisation can be kept within the linear perturbation regime, a prerequisite for the applicability of the linear polarisation resistance (LPR) method (Stern and Geary, 1957).

To validate the method, we compared our results to those derived from the EST method and standard reference techniques based on electrochemical measurements using embedded electrodes made from the same material or one analogous to the rebar being tested. Here, we applied the Integrated Network Sensors for Smart Corrosion Monitoring (INESSCOM) system (Alcañiz et al., 2016; Ramón, 2018), which measures the corrosion rate via a different electrochemical method to that of LPR (which relies on Tafel extrapolation from potentiostatic pulses). We also used linear

[1] The effective polarisation ($E_{POL}$) is the net increase in induced potential across the steel during the polarisation test, after compensating for the fall in potential due to the electrical resistance of the concrete and measurement system itself (IR-drop).

polarisation resistance (LPR), as per standard ASTM G59-97 (ASTM International, 2020), to take measurements on the INESSCOM embedded electrodes.

The DYN method was applied to reinforced concrete beams (25×18×75 cm) containing four longitudinal rebars of $\phi$10 mm and eight stirrups, $\phi$8 mm. Two beams for each concrete type, C30 and C80 ($f_{ck}$ = 30 MPa and 80 MPa according to EN 206), both using CEM I 42.5 R cement. The C30 type concrete (330 kg of cement; a/c = 0.60) had a 28-day mean compressive strength of 34 MPa, while the C80 type (500 kg of cement; a/c = 0.34) reached 88 MPa. The pertinent elements for the INESSCOM measurement cell, which were also used for the LPR measurements, were installed prior to concrete casting. The cell included two carbon steel electrodes ($\phi$10 mm, length 13 cm) placed in the centre of each beam, with the rebar forming the counter-electrode, and a reference electrode analogous to that of the DYN sensor.

The beams were cured for 28 days (20 °C, RH >95%) and then subjected to a flexural loading–unloading process to induce residual cracks (width ~0.2 mm). After 48 hours, the beams were partially submerged in a solution of artificial seawater (35 g/L NaCl). Figures 1(a) and (b) show examples of the test pieces.

Corrosion parameters were measured weekly for the first 6 weeks, and then every fortnight. We used the electronic equipment specific to the DYN and INESSCOM devices. For the DYN method, the equipment automatically adjusts the applied current throughout the measurement, providing real-time control over the effective polarisation potential ($E_{POL}$). This dynamic adjustment means that $E_{POL}$ can be maintained within the optimal range (5–30 mV) and verified at the end of each measurement using the recorded value. The control method and calculation applied in the DYN approach are described in detail in patent ES202130009 (Martínez and Ramón, 2021).

For the LPR technique, we used a PGSTAT 204 potentiostat to perform a potentiodynamic sweep of ±20 mV with respect to the corrosion potential ($E_{CORR}$) and at a rate of 0.167 mV/s.

We also took measurements following the DYN and EST methods while using the same portable device (Figure 1(c)). These comparative measurements were carried out on two concrete slabs of 50×50×10 cm with rebars of $\phi$8 mm and at a similar dosing as the C30 beams. One of the slabs was contaminated with 4% chloride (weight % with respect to the cement). After curing for 28 days (20 °C, RH >95%), we stored the slabs for a further 28 days under laboratory conditions and then performed six measurements per method on each slab.

(a) (b) (c)

Figure 1. (a) A segment of the beams placed in a saltwater bath after cracking; (b) Electrochemical measurements being conducted on the beams; (c) Application of the DYN and EST methods using the portable testing device developed by the authors.

## 3. RESULTS AND DISCUSSION

Figure 2 presents a comparison of the results from the DYN and EST methods based on spot measurements performed on the concrete slabs, one under passive conditions ($i_{CORR}$ <0.1 µA/cm²) and the other under actively corroding conditions ($i_{CORR}$ >1 µA/cm²).

For rebars with active corrosion, the EST method barely reached the minimum effective polarisation ($E_{POL}$ = 5 mV), whereas there was a significant overpolarisation in the passive rebars. The DYN method, on the other hand, maintained polarisation within the ideal range ($E_{POL}$ = 5–30 mV) in all cases, thanks to the dynamic adjustment of the applied current ($I_{AP}$). This adjustment translates into an increase in $I_{AP}$ for active rebars and a notable reduction in passive ones, compared to the EST method. Consequently, the values of $i_{CORR}$ measured using the EST technique tend to be higher than those from the DYN method.

The results demonstrate the importance of keeping the rebar polarisation within the linear perturbation regime, which is a necessary condition for the applicability of the linear polarisation resistance method. The overpolarisation observed when applying the EST method, especially in passive rebars, may distance the measurement from the linear perturbation regime and, therefore, introduce deviations in the estimation of $i_{CORR}$. The DYN method, by contrast, holds the polarisation within an appropriate range in all types of conditions, thus favouring a more consistent response. Furthermore, a lesser electrochemical perturbation is, in principle, associated with shorter recovery times to return to the initial corrosion potential, which helps reduce inspection times.

Figure 3 shows the evolution of the corrosion rate ($i_{CORR}$) in the beams, measured via different methods and recorded for more than 150 days after they were immersed in a saline solution. Measurements made over the first 20 days are quite disperse, possibly due to the different electrode arrangements: the DYN device uses surface electrodes, whereas the INESSCOM system and the LPR method are based on embedded electrodes.

Embedded sensor systems generally provide a more precise definition of the polarisation area, reducing a possible source of uncertainty associated with guard ring-based techniques. However, these systems are primarily limited by the actions required for their installation as they imply interventions on the concrete element in the case of existing structures, such as drilling of the concrete cover or local modification of the reinforcement (Figueira, 2017), options which are not always feasible in practice. On the other hand, surface probe-based techniques, such as the EST and DYN methods, eliminate this limitation and can be used for inspections and assessments without altering the concrete element.

After the initial period of divergence, there was good coherence between the methods, and the different evolutions of the beams made from C30 and C80 concrete are clearly evident. While C80 beams presumably have a denser, more compact matrix than C30 beams, the lower corrosion rates could be related to fewer cracks being induced during the loading process, given the C80 concrete's greater strength. At the end of the study, the values of $i_{CORR}$ in the C80 beams were between approximately 0.6 and 0.9 µA/cm², which is within the range associated with moderate corrosion (0.5–1 µA/cm²). The C30 beams had high corrosion rates (>1 µA/cm²) almost from the beginning of testing, and consistently across the three methods.

Overall, the results show that the DYN method, by maintaining appropriate polarisation conditions, provides consistent measurements across a wide range of corrosion states and yields results comparable with those of standard testing techniques based on embedded sensors. The non-invasive nature of the probe used in the DYN method further enhances its potential as an in-situ inspection tool, particularly in existing structures where the installation of embedded sensors may not always be feasible.

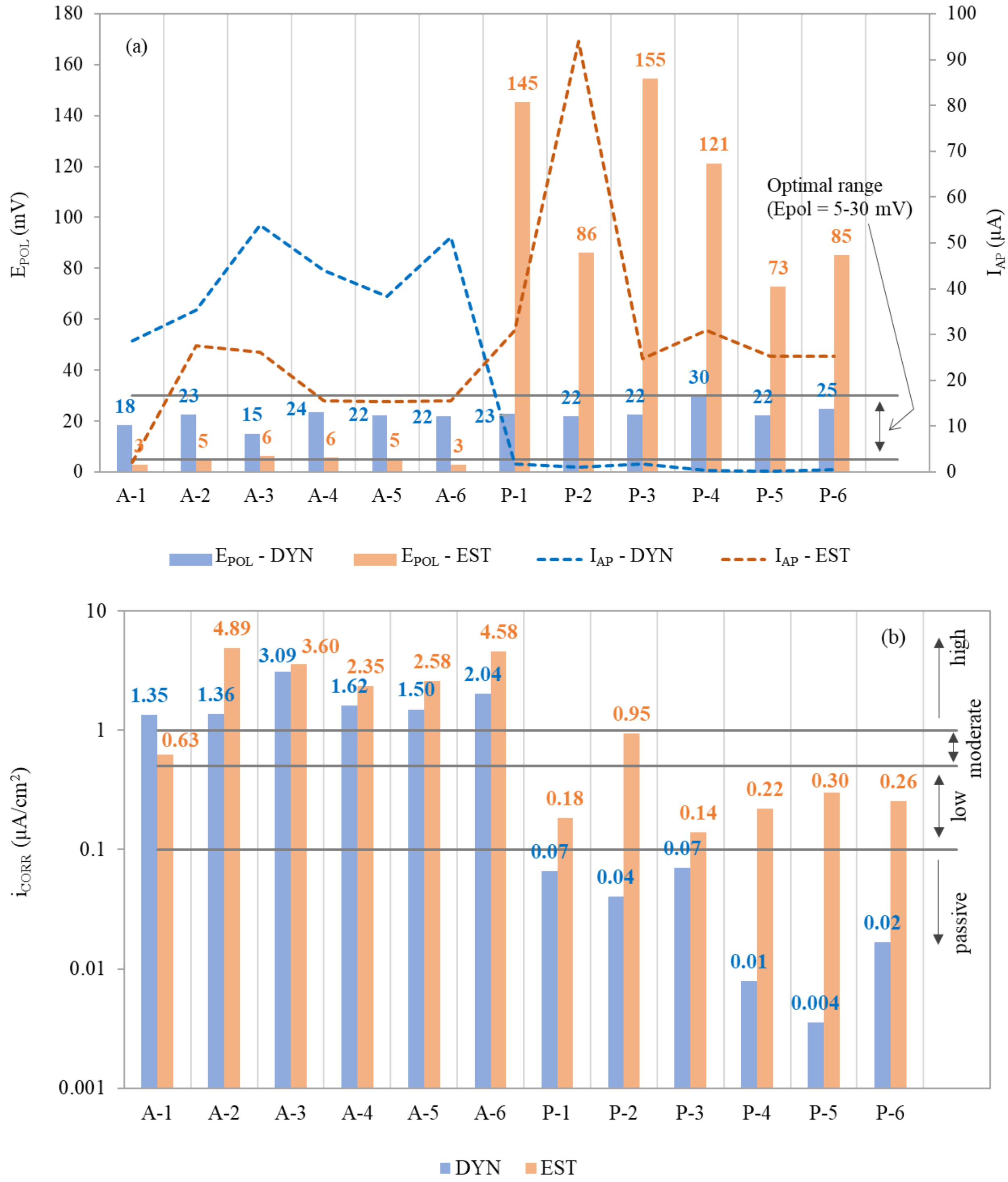


Figure 2. Comparison of the measurements taken with the DYN and EST methods in active (A) and passive (P) rebars in two slabs of concrete: (a) applied current ($I_{AP}$) and rebar polarisation ($E_{POL}$); and (b) the resulting corrosion rate ($i_{CORR}$), including the corresponding levels of corrosion for $i_{CORR}$ established in UNE 112072:2011 (AENOR, 2011).

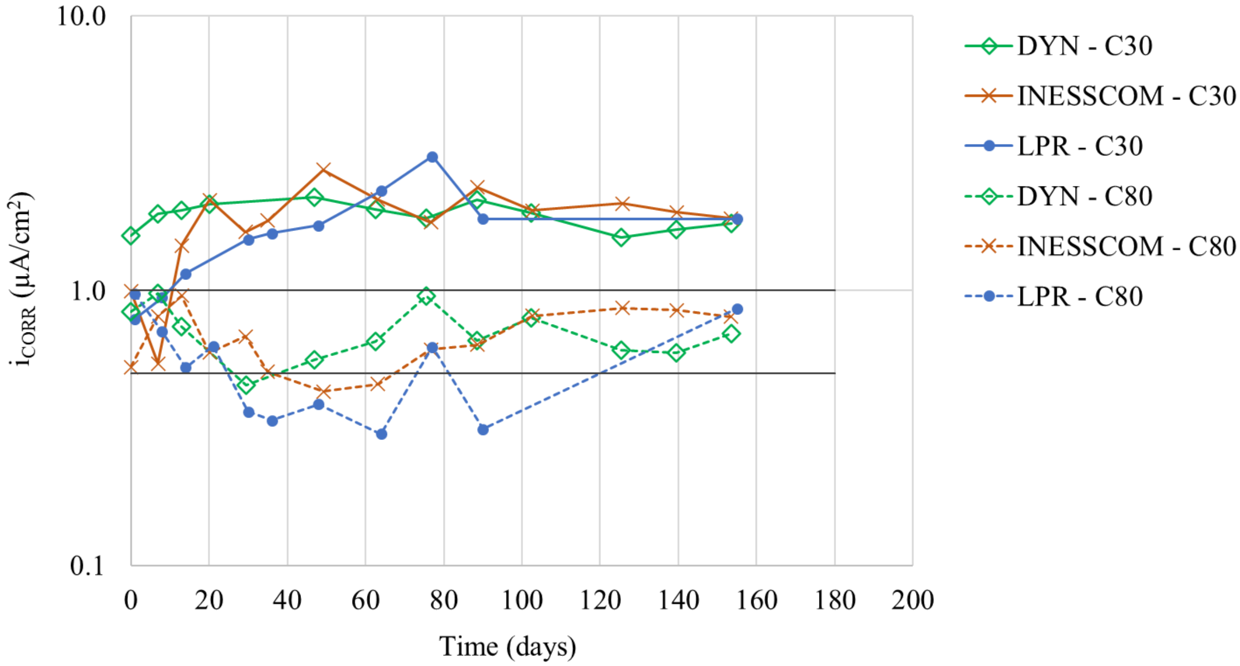


Figure 3. Evolution of corrosion rate ($i_{CORR}$) in reinforced concrete beams according to three different methods. The graph shows the average results for each type of concrete and measurement technique. The corresponding levels of corrosion for $i_{CORR}$ as defined in UNE 112072:2011 (AENOR, 2011) are shown on the right.

## 4. CONCLUSIONS

This study presents a new method for the inspection of corrosion in reinforced concrete structures, based on dynamically controlled confined galvanostatic current. The probe used allows direct assessment of the reinforcement without the need for embedded electrodes, reducing the invasiveness of the procedure and enabling rapid and operationally efficient inspections. The experimental results show significant improvements compared to previous generations of confined galvanostatic current systems, particularly under boundary conditions where the new technique maintains polarization within the optimal range, ensuring the applicability of the linear polarization resistance method. Furthermore, the corrosion rate values obtained are comparable to those measured using standard techniques and allow differentiation between different levels of corrosion in cracked elements. These findings highlight the strong potential of the method as a tool for structural diagnosis, particularly in existing structures, although it still needs to be validated in real-world conditions to consolidate its applicability.

## 5. ACKNOWLEDGEMENTS

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