

Propagation of chloride induced corrosion in reinforced concrete structures after application of an external thermal insulation system

M. Gastaldi, A.G. Mainini

The application of an External Thermal Insulation Composite System (ETICS) to enhance the energy efficiency of buildings can significantly affect the penetration of aggressive agents (such as chlorides, CO₂, water, etc.), thereby mitigating the degradation processes of reinforced concrete structures. ETICS can also be implemented on existing structures where reinforcement corrosion has already initiated, but the concrete still appears sound and no inspection have been carried out to assess the condition of the structure. This paper reports the results of an experimental study on the effects of ETICS on reinforced concrete elements contaminated by chlorides, in which corrosion had already initiated. The specimens were subjected to accelerated wet/dry cycles to simulate atmospheric exposure conditions. The findings indicate that the insulated specimens exhibit a progressive drying behavior over time, which contributes to slowing down the corrosion propagation of the reinforcement.

KEYWORDS: CHLORIDE INDUCED CORROSION, CORROSION PROPAGATION, REINFORCED CONCRETE, THERMAL INSULATION SYSTEM, ACCELERATED TESTS;

INTRODUCTION

Recent demands for reducing the energy consumption of buildings [1] have led to a significant increase in strategies and initiatives aimed at improving the existing building stock. In this context, the application of an External Thermal Insulation Composite System (ETICS) represents one of the most effective solutions for decreasing the energy impact of buildings. External insulation is commonly used not only to improve the thermal transmittance of the building envelope, but also to mitigate thermal bridging, which is particularly relevant in the case of exposed reinforced concrete structures, a typical example in many buildings.

Before installing this thermal insulation system, it is recommended to inspect the existing structures to ensure there are no underlying issues that could lead to the deterioration of the elements concealed by the insulation system. The presence of external cladding may mask ongoing degradation processes and, in some cases, may even accelerate them; moreover, such degradation can reduce the effectiveness of the insulation itself.

In the case of reinforced concrete structures, which

Matteo Gastaldi

Politecnico di Milano, Dipartimento di Chimica, Materiali e Ingegneria
Chimica "Giulio Natta". Milano, Italia

Andrea Giovanni Mainini

Politecnico di Milano, Dipartimento di Architettura, Ingegneria delle
Costruzioni e Ambiente Costruito, Milano, Italia

constitute a large proportion of Italy's building heritage, the predominant degradation mechanisms involve the corrosion of steel reinforcement, particularly corrosion induced by carbonation and chlorides [2]. Consequently, when planning energy efficiency improvements through the application of ETICS on existing buildings, it is essential to carry out detailed inspections to assess the condition of the embedded reinforcement (whether corrosion is in the initiation or propagation phase and whether chlorides are present), in order to determine whether repair works are needed to ensure that the residual service life of the structure can be achieved [3]. Nevertheless, in practice, unless a building displays visible signs of degradation, insulation systems are often installed without any prior evaluation of the condition of the structure.

In buildings constructed several decades ago, carbonation and chloride penetration may have already reached the steel reinforcement and corrosion processes have already initiated, even if no visible signs of damage (such as cracking) have yet manifested. In such cases, the application of ETICS may either promote or decrease corrosion propagation. Previous studies have analysed the effects of ETICS installation on reinforced concrete structures affected by carbonation [4, 5]. These investigations, based on laboratory experiments and field measurements, have shown that insulation systems can help reduce the moisture content in concrete, thereby mitigating the propagation of carbonation-induced corrosion. However, the reduction in moisture content is not immediate and depends on the properties of the concrete and the environmental conditions within the building (since the low vapor permeability of the insulating material limits moisture exchange with the exterior). During this transitional period, the presence of an ETICS may worsen the condition. This is due in part to the system's application process, which typically involves cement-based mortars that can increase the moisture content of the substrate. It is important to note that these studies did not directly measure the reinforcement corrosion but inferred it based on the concrete's moisture levels.

The present study aims to investigate the effect of ETICS application on the propagation of chloride-induced corrosion, in order to assess the possible consequences

of energy efficiency retrofit on buildings located in marine environments where corrosion has not yet manifested but has already been initiated. To this end, reinforced concrete specimens were cast with chlorides mixed-in to initiate corrosion on steel reinforcement. An ETICS system was applied to the specimens, consisting of expanded polystyrene (EPS) panels with added graphite, with a 15% recycled material content. Two configurations were tested: one with a continuous panel and one with joints between panels. The specimens were then subjected to wet/dry cycles to simulate atmospheric conditions in an accelerated manner. The results of the experimental work provide insights into how ETICS influences the thermo-hygrometric behavior of concrete and the corrosion condition of embedded reinforcement.

EXPERIMENTAL PROCEDURE

Three prismatic reinforced concrete samples 40×40×5 cm³ were realised. The concrete was prepared mixing 358 kg/m³ of limestone cement (type CEM II/B-L 32,5R), 215 l/m³ of water (water/cement ratio of 0.60) and 1745 kg/m³ of aggregates (\emptyset max = 12.5 mm). 1% chlorides by mass relative to the cement, in the form of NaCl, was added to the mixing water.

Each specimen contained three B450C-type reinforcement bars, which were sandblasted and cleaned with alcohol before casting. The bars were positioned to ensure a concrete cover of 20 mm. Both ends of each bar were masked using Teflon tape and adhesive heat-shrink tubing, leaving only a central portion of 30 cm in contact with the concrete. An activated titanium reference electrode (Ti) was fixed in correspondence with each reinforcement bar, and a probe for measuring the electrical resistivity of the concrete was placed in the middle of each specimen. This probe allowed for resistivity measurements at different cover depths: 10 mm (position I), 20 mm (position II), and 30 mm (position III). The cell constant of each probe was determined experimentally prior to use.

After casting, the specimens were cured in their molds for 7 days and then stored in the laboratory. Approximately two weeks later, the ETICS was applied to two specimens. The insulation system was installed as follows: 1) application of a commercial cement-based adhesive/render on the concrete surface; 2) installation of a 12 cm-

thick EPS insulation panel with added graphite and 15% recycled material (ETICS); 3) application of a 2-3 mm layer of the same cementitious render over the EPS surface, embedding within it a fiberglass mesh with a 3.5 × 3.8 mm² grid; 4) application of two layers of paint (based on acrylic, silicate, and silicone resins).

Finally, the lateral surfaces (40×5 cm²) of all specimens were sealed with epoxy resin. In the two specimens with ETICS, the resin was also extended to cover approximately one-third of the EPS panel. In one of the two ETICS specimens, the insulation was installed to simulate a joint area between panels by assembling four 20 × 20 cm² EPS pieces side by side. Figure 1 shows the completed specimens and selected phases of the ETICS installation process.

Type J thermocouples were also installed to measure

temperature in various positions within the three specimens (Fig. 2). In particular, the sensors were placed on the surface of the uncoated specimen (Sup.), within the concrete (A2 and A3), inside the adhesive layer (B1 and B3), and in the joints between the insulation panels (C3). Additionally, one thermocouple was positioned near the specimens, in a sheltered location, to monitor ambient temperature (Amb.).

The specimens were positioned vertically (Fig. 2) to simulate a vertical wall. The coated faces, along with one face of the uncoated specimen, were subjected to dry/wet cycles consisting of: 45 hours of heating using 150 W infrared (IR) lamps placed at a distance of 35 cm (producing surface temperatures exceeding 40°C), followed by 3 hours of wetting using tap water spray at a rate of 0.5 l/m²·min (applied with 360° irrigation nozzles).

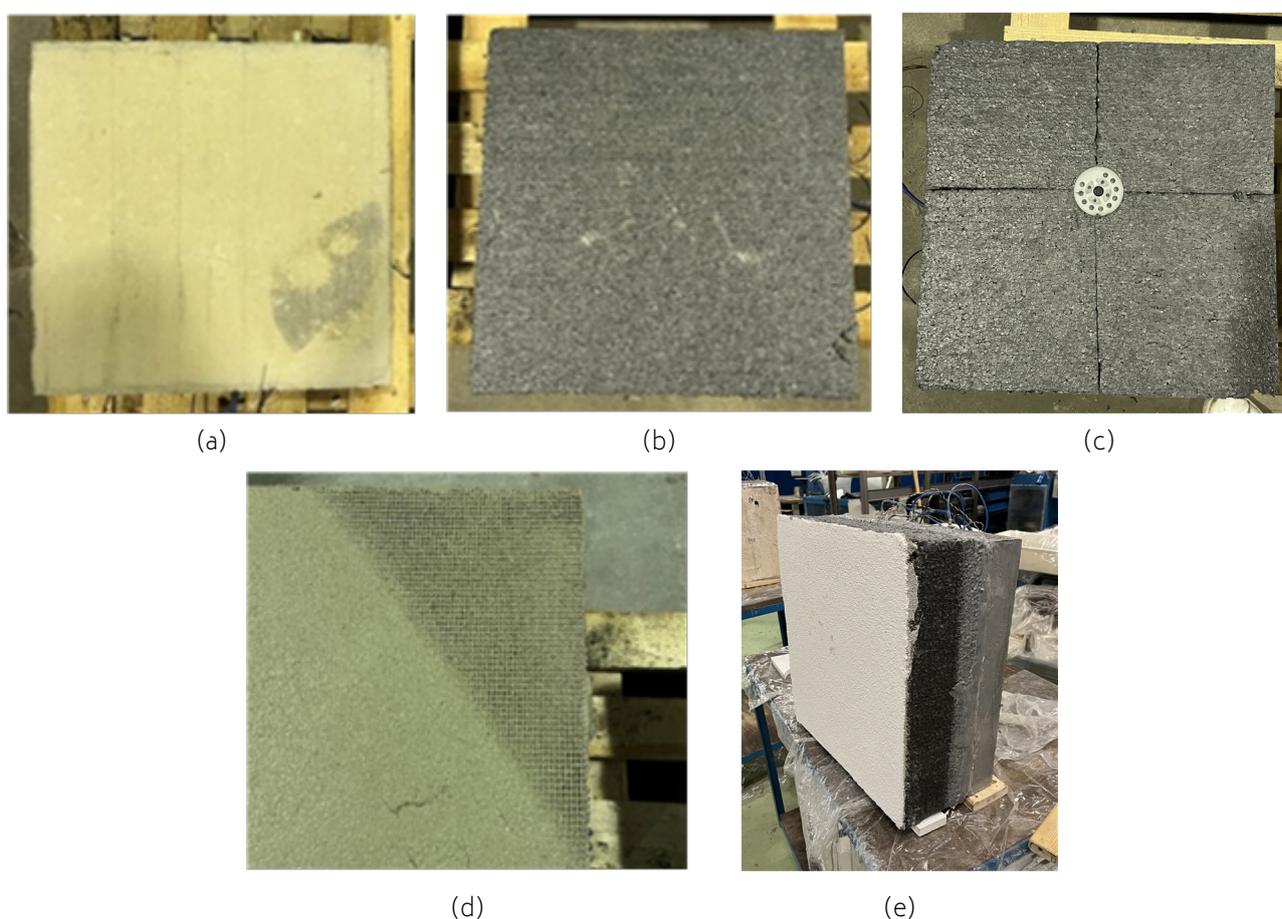


Fig.1 - ETICS installation phases: a) concrete specimen without coating; b) sample with continuous EPS panel; c) sample with jointed EPS panel; d) installation of the render with embedded glass fiber mesh; e) sample at the end of installation
/ *Fasi di posa dell'ETICS: a) provino in calcestruzzo senza rivestimento; b) provino con il pannello di EPS continuo; c) provino con il pannello di EPS giuntato; d) posa del rasante con la rete in fibra di vetro inglobata; e) provino al termine della posa.*

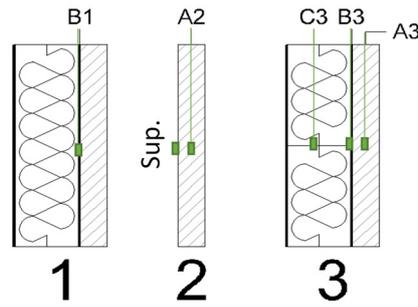


Fig.2 - Schematic representation of the position of the Type J thermocouples in the specimens / *Rappresentazione schematica della posizione delle termocoppie nei provini.*

This setup was designed to simulate atmospheric conditions in an accelerated manner.

A 10-minute interval was required between cycles to prepare for the next phase (positioning the IR lamps, setting up the wetting system, and taking some measurements). A total of 12 cycles were performed.

The side of each specimen opposite the one exposed to

the cycles, which remained unshielded, was left under laboratory conditions to simulate the interior wall of a building. To confine both the water spray and the heat from the IR lamps, polypropylene corrugated sheets were placed along the lateral surfaces of each specimen. Figure 3 shows the specimens during both phases of the cycle.

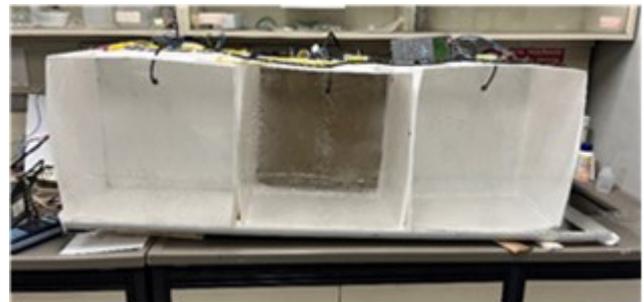


Fig.3 - Drying cycle with IR lamps (left) and wetting cycle with water spray through 360° jet nozzles (right) carried out on the specimens / *Ciclo di asciugatura con lampade a IR (a sinistra) e ciclo di bagnato con spruzzo d'acqua tramite ugelli con getto a 360° (a destra) realizzati sui provini.*

The first wetting cycle was preceded by a laboratory exposure period of approximately two weeks (at around 23°C and 40% relative humidity) and by about one week of drying using IR lamps.

During the cycles, the free corrosion potential of the reinforcement was measured using the activated titanium electrodes, along with the concrete resistivity at different cover depths and the temperature at various points monitored by the thermocouples. Additionally, the corrosion rate of the reinforcement was measured using the linear polarization technique before starting the cycles, during the final wetting cycle, and at the end of the testing period.

RESULTS AND DISCUSSION

Figure 4 shows the time evolution of the average corrosion potentials measured on the three reinforcement bars embedded in each specimen, as well as the electrical resistivity of the concrete measured at the level of the reinforcements (20 mm concrete cover depth, position II). It can be observed that, initially, the specimens with ETICS, both continuous and with panel joints (specimens 1 and 3, respectively), exhibit lower corrosion potentials and resistivity values at the reinforcement level compared to the uncoated specimen (specimen 2). This difference can be ascribed to the installation phase of the insulation system,

which increases the surface moisture of the concrete (due to the use of a cement-based adhesive). The presence of the ETICS also limits the evaporation of water from the specimens. Therefore, during the initial phase in which the specimens were kept under dry conditions (laboratory storage followed by IR heating), the corrosion potential and resistivity in specimen 2, without coating, tend to increase over time, while in specimens 1 and 3 (coated), the increase is

less pronounced. In specimen 2, the potential increases from -235 mV vs Ti to -180 mV vs Ti, and the resistivity rises from 65 $\Omega \times m$ to 485 $\Omega \times m$. In specimens 1 and 3, by contrast, the increase in potential is limited to 20-30 mV, and the resistivity increases by only 80-110 $\Omega \times m$.

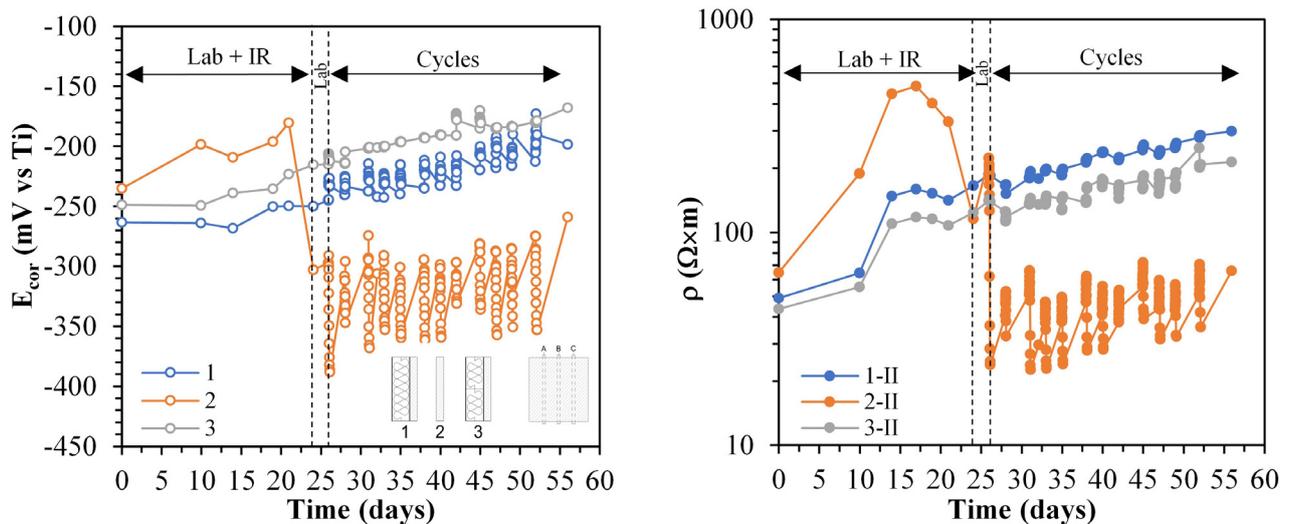


Fig.4 - Mean values of the corrosion potentials measured on the three rebars present in each specimen (left) and concrete electrical resistivity (right) at reinforcement surface level (20 mm depth in the concrete cover) / *Valori medi dei potenziali di corrosione misurati sulle tre armature presenti in ogni provino (a sinistra) e resistività elettrica del calcestruzzo (a destra) a livello della superficie delle armature (20 mm di profondità nel copriferro).*

Table 1 reports the corrosion rates measured during the initial laboratory exposure phase. The values show that all reinforcements in the three specimens were experiencing non-negligible corrosion (corrosion rate > 1-2 $\mu m/year$), due to the presence of chlorides added during casting (the variability among the corrosion rates of the rebars in the same sample can be attributed to the mechanism of chloride-induced corrosion). The average corrosion rates in specimens 1, 2, and 3 were 10.5 $\mu m/year$, 3.6 $\mu m/year$, and 12.6 $\mu m/year$, respectively. These results are consistent with the corrosion potential and resistivity measurements; the uncoated specimen (2), which dries out more effectively, shows lower corrosion rates compared to the coated specimens (1 and 3), which retain more moisture and thus promote more intense corrosion. During the first wetting cycle, a sharp decrease in both

the corrosion potential and the resistivity measured at the reinforcement level is observed in specimen 2, which does not have ETICS (Fig. 4). The potential drops from -290 mV vs Ti to -390 mV vs Ti, and the resistivity falls from approximately 200 $\Omega \times m$ to 20 $\Omega \times m$. This demonstrates that the 3-hour wetting phase is effective in raising the moisture level of the concrete at the depth of the reinforcement to conditions that strongly favour rapid corrosion propagation.

In specimens 1 and 3, however, no significant effects are observed as a result of the 3-hour intensive wetting phase. The presence of the ETICS effectively prevents an increase in concrete moisture, even in the case where the EPS panel is discontinuous (specimen 3).

The application of the dry/wet cycles in specimen 2 results

in continuous fluctuations between dry conditions, where potentials and resistivity values are around -300 mV vs Ti and $70 \Omega \times m$, respectively, and wet conditions, with values of -360 mV vs Ti and $20-30 \Omega \times m$. These variations repeat over time with each cycle, without showing a significant long-term decrease in either potential or resistivity. This indicates that the 45-hour IR heating period is only sufficient to restore the specimen's moisture level to the pre-wetting condition, but does not cause a progressive drying of the concrete.

In contrast, specimens 1 and 3 show a gradual increase in both potential and resistivity at a depth of 20 mm over time, despite repeated wetting cycles. The two specimens follow a similar trend and reach final values of corrosion potential above -200 mV vs Ti and resistivity exceeding $200 \Omega \times m$. This suggests that the specimens are drying progressively over time, likely due to moisture evaporation through the uncoated rear face of the samples, which is in equilibrium with the laboratory environment.

During the cycles, temperature was also monitored at various points. Figure 5 presents the measurement results (some of which were acquired using a data acquisition system) recorded over time by the different thermocouples. The ambient temperature in the laboratory (Amb), measured near the specimens, shows a small fluctuation over time due to both indoor climate control (heating by radiators, which were not active during the night) and the heat generated by the infrared (IR) lamps

(which also warmed the surrounding air), varying between $20^{\circ}C$ and $29^{\circ}C$ during lamps operation.

A similar trend was observed with the thermocouples placed inside the adhesive layer (B1 and B3), beneath the EPS panel, and within the concrete of specimen 3 (A3). The fact that the same temperatures were recorded by probes B1 and B3 indicates that the presence of panel joints does not affect the thermal insulation performance of the system at the concrete surface.

The temperature measured in the joint between EPS panel segments (C3), located roughly halfway through the panel thickness, was more sensitive to the cycles, though variations remained minor, ranging between $19^{\circ}C$ and $31^{\circ}C$.

On the surface of the concrete (Sup), temperatures reached around $15^{\circ}C$ at the end of the wetting phase and approximately $45^{\circ}C$ during the IR heating period. The temperature within the concrete of the specimen without ETICS (A2) followed a trend similar to that observed at its surface (Sup). Only a slight delay is observed in the temperature variation, and the concrete reaches lower temperatures, down to $12.5^{\circ}C$, at the end of the wetting cycle, and occasionally higher temperatures during the dry phase, due to the thermal properties of the concrete. The temperature difference between the interior of the concrete and the surrounding environment induces a heat flux across the full thickness of specimen 2.

Tab.1 - Corrosion rate, in $\mu m/year$, measured 10 days after the start of the tests (second measurement point in Fig. 4) / *Velocità di corrosione, in $\mu m/anno$, misurate 10 giorni dopo l'inizio delle prove (secondo punto di misura in Fig. 4).*

Sample	1	2	3
Rebar A	10.9	2.1	7.1
Rebar B	10.8	4.6	21.0
Rebar C	9.9	4.1	9.7
Mean	10.5	3.6	12.6

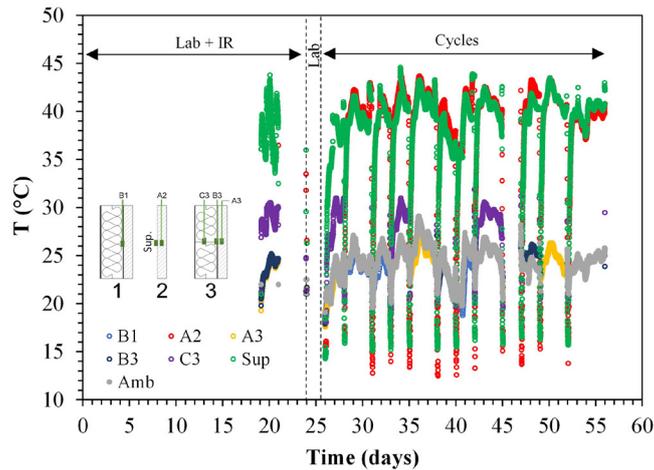


Fig.5 - Temperature measured with the thermocouples (placed in the samples, on a sample -Sup- and in the laboratory -Amb-) during the test / *Temperatura rilevata con le termocoppie (poste nei campioni, su un campione -Sup- e nel laboratorio -Amb-) durante le prove.*

The analysis of resistivity at different depths within the concrete cover shows that zones with varying moisture levels are present in the concrete, this can lead to different corrosion conditions. Figure 6 shows the resistivity measured over time at 10 mm (I), 20 mm (II), and 30 mm (III) of cover depth in samples 1 and 2. In sample 1, with ETICS, the resistivity exhibits a continuous increase at all depths; the probe at 30 mm depth (probe III) shows a more marked increase, reaching approximately 450 $\Omega \times m$ by the end of the test. The probes at the other depths (probes I and II) reveal modest differences, with values reaching just under 300 $\Omega \times m$ by the end of the test. This indicates that water evaporation occurs primarily from the rear side of the sample, which is exposed to laboratory conditions,

and that the reinforcement bars, located between 20 and 30 mm in depth, are in contact with slightly more humid concrete in the upper part, due to the surface coating, and drier concrete in the lower part. No effects of the wet/dry cycles were observed on the measurements taken at different depths. Sample 3 showed behavior similar to that of sample 1, confirming that the presence of joints does not affect the performance of the surface coating. In contrast, sample 2 clearly shows the impact of the wet/dry cycles on the resistivity measured at all analysed cover depths (Fig. 6, right). The most significant fluctuations were observed in probes I and II, which are positioned closer to the exposed surface of the sample and therefore more directly affected by the wet/dry cycles.

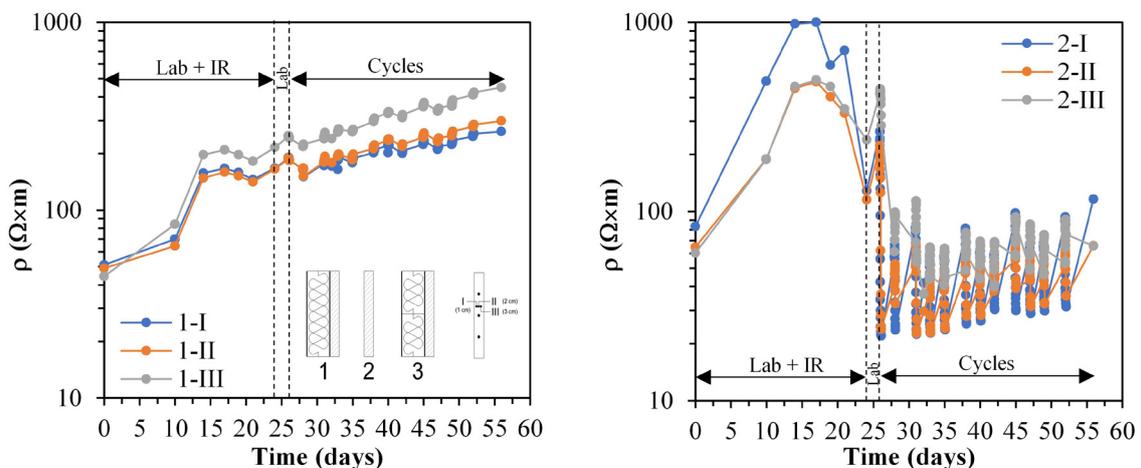


Fig.6 - Concrete electrical resistivity measured at different depths of the concrete cover in specimen 1 (left), with continuous EPS insulating coating, and in specimen 2, without coating (right), during the tests / *Resistività elettrica del calcestruzzo misurata a diverse profondità del copriferro nel provino 1 (a sinistra), con rivestimento isolante continuo in EPS, e nel provino 2, senza rivestimento (a destra), durante le prove.*

An analysis of a single wetting cycle reveals that in the uncoated sample, the resistivity measured at a depth of 10 mm (probe I) exhibits an immediate and progressive decrease as soon as water spraying begins, dropping from $60 \Omega \times m$ to approximately $20 \Omega \times m$ after around two hours (Fig. 7, right). In contrast, probes II (20 mm) and III (30 mm) initially show a slight increase in resistivity. This behavior can be attributed to the heat flux that develops across the sample during the initial phase of the cycle (as reported above). At the onset of wetting, both the surface and the interior of the concrete are at approximately $40^\circ C$. As water is applied, the concrete surface cools rapidly, while the inner layers retain higher temperatures (Fig. 7, bottom), with a difference exceeding $5^\circ C$ (as recorded by thermocouples Sup and A2). This thermal gradient persists for nearly two hours.

In sample 2 the resistivity at 20 mm depth, correspon-

ding to the reinforcement level, begins to decrease after roughly 30 minutes, eventually aligning with the values recorded by probe I after approximately 2.5 hours. Measurements from probe III begin to decline after about 50 minutes and return to their initial values by the end of the wetting cycle.

The corrosion potential of the reinforcements in sample 2, initially at $-300 mV$ vs Ti, begins to decline about 10 minutes after the start of wetting, stabilizing around $-350 mV$ vs Ti after two hours (Fig. 7, left).

In contrast, the samples equipped with ETICS show no significant response to the wetting phase. No substantial variations are observed in the values of corrosion potential, resistivity, or temperature (either on the surface or within the concrete) during the 3-hour water spraying period.

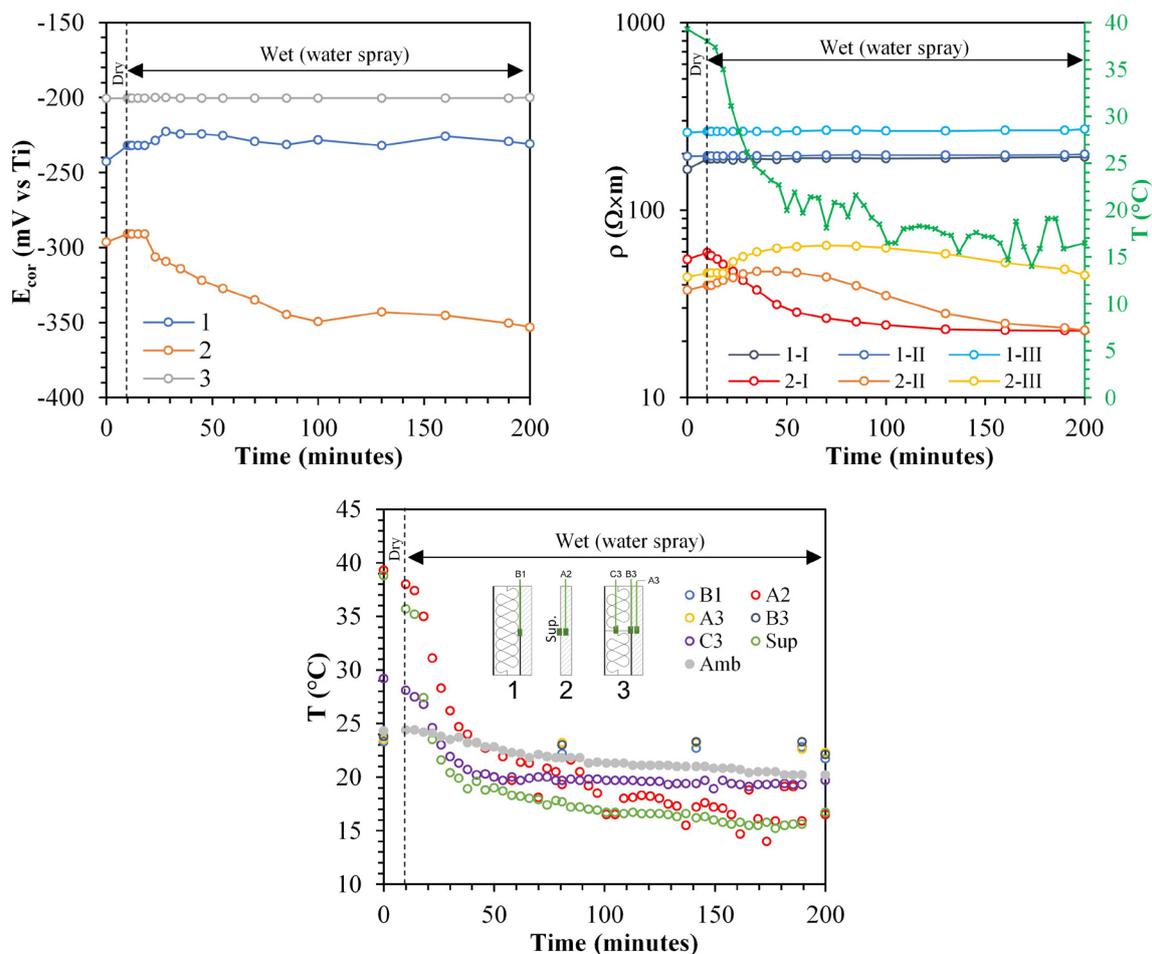


Fig.7 - Mean values of the corrosion potentials measured on the three rebars present in each specimen (top left), concrete electrical resistivity at different depths in the concrete cover (top right) and temperature (bottom) measured during a wet cycle / *Valori medi dei potenziali di corrosione misurati sulle tre armature presenti in ogni provino (in alto a sinistra), resistività elettrica del calcestruzzo a diverse profondità nel copriferro (in alto a destra) e temperatura (in basso) misurate durante un ciclo di bagnato.*

Corrosion rate measurements taken during the final wetting cycle and at the end of the testing period reveal an increase in reinforcement corrosion in the uncoated sample, with values rising from approximately $4 \mu\text{m}/\text{year}$ (measured before the start of the cycles) to over $15 \mu\text{m}/\text{year}$ (Fig. 8). In contrast, both samples with ETICS show reinforcement corrosion rates that are more than halved compared to the initial values (with average values dropping from about $10 \mu\text{m}/\text{year}$ to less than $4.5 \mu\text{m}/\text{year}$, with some reinforcements showing values below $2 \mu\text{m}/\text{year}$).

This demonstrates that the presence of ETICS is effective in mitigating reinforcement corrosion (increase of the corrosion potential and decrease of the corrosion rate), promoting the drying of the concrete. However, it is important to consider that chloride-induced corrosion can continue to propagate, and achieving conditions that fully arrest corrosion is not straightforward. Additionally, over time, the effectiveness of the ETICS may deteriorate due to material degradation [6], which could compromise the positive effect on reinforcement corrosion.

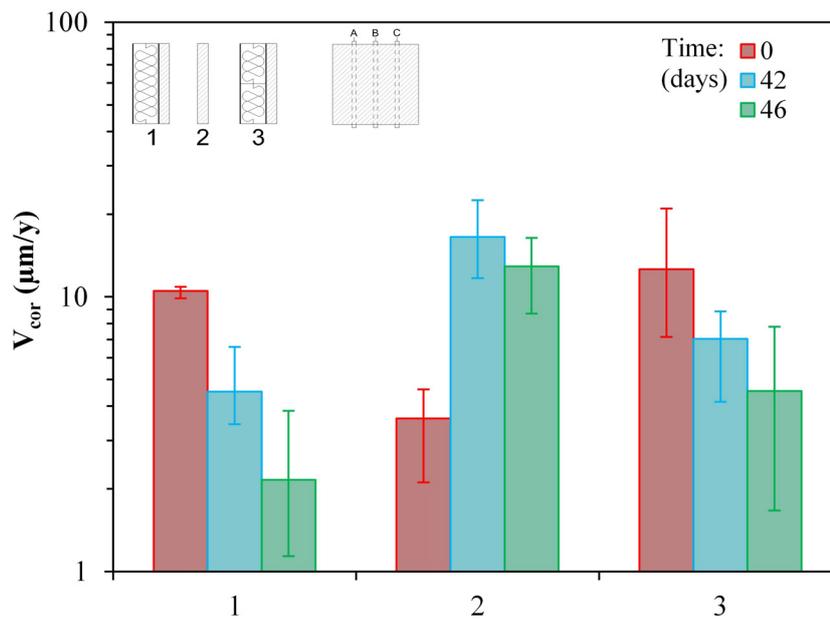


Fig.8 - Mean values, and range of variability in the results of the corrosion rates of the reinforcement in the specimens, with and without ETICS, before carrying out the dry/wet cycles, during the last wet cycle (42 days) and at the end of the tests (46 days) / *Valori medi e intervallo di variazione dei risultati delle velocità di corrosione delle armature nei provini, con e senza ETICS, prima dello svolgimento dei cicli di asciutto/bagnato, durante l'ultimo ciclo bagnato (42 giorni) e al termine delle prove (46 giorni).*

CONCLUSIONS

The experimental tests showed that the application of an external thermal insulation composite system (ETICS), aimed at improving the energy efficiency of buildings, can also be effective in reducing reinforcement corrosion in chloride-contaminated concrete.

Even after exposure to 12 dry/wet cycles (each consisting of 45 hours of heating at over 40°C followed by 3 hours of intense tap water spraying), used to simulate severe environmental conditions in an accelerated manner, the reinforcement embedded in concrete with 1% chlorides by cement mass and coated with ETICS exhibited an in-

crease in corrosion potential and a reduction in corrosion rate over time, due to the continuous and gradual drying of the concrete. Corrosion rates were more than halved compared to the initial values (dropping from approximately $10 \mu\text{m}/\text{year}$ to below $4.5 \mu\text{m}/\text{year}$, with some reinforcements showing values below $2 \mu\text{m}/\text{year}$).

By contrast, the reinforcement in uncoated concrete experienced a drop in corrosion potential of over 100 mV and more than a threefold increase in corrosion rate, reaching values greater than $15 \mu\text{m}/\text{year}$ after the cycles.

Thus, beyond thermal benefits, the use of ETICS can provide advantages in terms of the durability of reinforced

concrete structures. However, in cases of chloride-induced corrosion, it must be emphasized that although a reduction in corrosion activity can be achieved, complete

arrest is difficult. Additionally, the potential degradation of the ETICS over time should be taken into account, as it may compromise its long-term effectiveness.

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Propagazione della corrosione da cloruri in strutture in calcestruzzo armato in seguito all'applicazione di un sistema d'isolamento termico esterno

L'applicazione di un sistema d'isolamento termico a cappotto esterno per migliorare l'efficienza energetica degli edifici può influenzarne la penetrazione di sostanze aggressive (cloruri, CO₂, acqua, ecc.), rallentando così il degrado delle strutture in calcestruzzo armato. Il sistema a cappotto può venire applicato anche su strutture esistenti in cui si è già innescata la corrosione sulle armature, ma in cui il calcestruzzo appare ancora sano e quindi non sono state svolte indagini per valutarne le condizioni di conservazione. In questo lavoro sono riportati i risultati di un lavoro sperimentale sugli effetti di un sistema d'isolamento a cappotto su elementi in calcestruzzo armato contaminati da cloruri in cui la corrosione si è già innescata. I provini sono stati soggetti a cicli di asciutto/bagnato, in modo da simulare, in modo accelerato, le condizioni atmosferiche. I risultati mostrano che i campioni con il cappotto tendono ad asciugarsi nel tempo, riducendo la propagazione della corrosione delle armature.

PAROLE CHIAVE: CORROSIONE DA CLORURI, PROPAGAZIONE CORROSIONE, CALCESTRUZZO ARMATO, SISTEMA DI ISOLAMENTO TERMICO A CAPPOTTO, PROVE ACCELERATE;

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