



Article

A Combined Experimental and Analytical Analysis of the Prediction of the Bonding Strength in Corroded Reinforced Concrete Through Half-Cell Potential Measurements

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Abstract

This study examines the relationship between bond strength degradation in corroded reinforced concrete and Half-Cell Potential (HCP) measurements through a combined experimental and numerical approach. Fifty-four concrete specimens reinforced with D19 and D22 rebars underwent impressed-current corrosion to induce specific levels of mass loss. The experimental results showed a progressive reduction in bond strength with increasing corrosion; at approximately 20% mass loss, D19 specimens exhibited up to ~45% reduction, while D22 specimens showed a reduction in ~30%. Correspondingly, HCP values became more negative as corrosion intensified, shifting from around −200 mV at 0% corrosion to values below −900 mV at higher corrosion levels. Although HCP effectively reflected corrosion severity, it did not correlate linearly with bond strength degradation. Numerical simulations performed using COMSOL Multiphysics reproduced the observed electrochemical trends, demonstrating increasingly negative potential distributions with higher corrosion current densities. The findings confirm that HCP is a reliable indicator of corrosion activity but has limited predictive capacity for bond strength loss. This work contributes quantitative insight into the electrochemical–mechanical relationship in corroded reinforced concrete and supports the development of improved assessment frameworks for early maintenance and structural integrity evaluation.



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1. Introduction

Reinforced concrete is widely used in buildings, bridges, and transportation infrastructure due to its strength, durability, and cost-efficiency [1]. However, its large-scale production especially of cement has substantial environmental impacts, contributing approximately 8% of global CO₂ emissions throughout its life cycle, from raw material extraction to demolition [2]. This growing concern shows how important it is to make reinforced concrete structures durable and sustainable by incorporating innovative methods like non-destructive testing (NDT). Ensuring its longevity will help reduce carbon emissions, conserve resources, and lessening the long-term environmental damage of making and throwing away concrete [3].

Chloride-induced steel corrosion in reinforced concrete has a substantial effect on the global economy. The monetary cost of corrosion has been estimated to represent approximately 3–4% of the global GDP [4,5], reflecting the considerable financial impact associated with material degradation across industrial, transportation, and civil infrastructure systems. When applied to current global economic output, this percentage corresponds to several trillion US dollars in annual losses, excluding indirect costs such as environmental impacts, operational disruptions, and premature repair or rehabilitation requirements. Corrosion progresses internally and gradually, making early detection difficult through visual inspection and emphasizing the need for reliable diagnostic methods. Timely identification and intervention are essential to prevent costly structural damage and maintain the integrity of reinforced concrete systems. The magnitude of this economic burden underscores the necessity of developing effective corrosion management strategies and adopting assessment techniques capable of supporting preventive maintenance and extending the service life of critical infrastructure.

Multiple study [6,7] have investigated the impact of corrosion on the bond strength between concrete and steel reinforcement. Researchers have shown that corrosion substantially weakens the mechanical properties of reinforced concrete, especially its bond strength [8]. The corrosion process initiates when anodic and cathodic regions develop at the interface of steel and concrete. Steel undergoes oxidation at the anodic area, indicating that iron (Fe) reacts with water (H₂O) and external chloride ions (Cl[−]). This reaction produces iron ions (Fe²⁺) and frees electrons:



The electrons move along the steel reinforcement to the cathodic area, where they facilitate a process that enhances reduction. As demonstrated in Equation (2), at the steel interface, electrons react with water molecules to form hydroxide ions (OH[−]) when oxygen (O₂) and water (H₂O) are present.



As the oxidation reaction goes on, iron ions (Fe²⁺) in the anodic region combine with chloride ions (Cl[−]) and water to make iron hydroxide (Fe(OH)₂), which results in the increase in volume. This expansion causes tensile stress at the steel-concrete interface, which causes the concrete to crack and spall. Rust creates tensile stress that speeds up the breakdown of the bond between steel and concrete. If this is not fixed, it can lead to structural failure [9].

NDT is a safe way to test concrete condition without damaging them. The measurement of Half-Cell Potential (HCP) is a well-established, non-destructive technique for evaluating the electrochemical potential of steel reinforcement in concrete, among other approaches [10–12]. It gives essential information about how bad the corrosion is without needing a lot of physical samples, which is critical for in situ assessment [11]. HCP measures the difference in electrical potential between the rebar embedded in the concrete and a reference electrode on the surface of the concrete. The HCP setup usually has a high-impedance voltmeter, a rebar as the working electrode, and a reference electrode (such Cu/CuSO₄ or Ag/AgCl) for stable potential comparison. The conducting wire of the voltmeter connects the rebar and the reference electrode, which completes the electrical circuit and makes it possible to measure the potential difference, as shown in Figure 1.

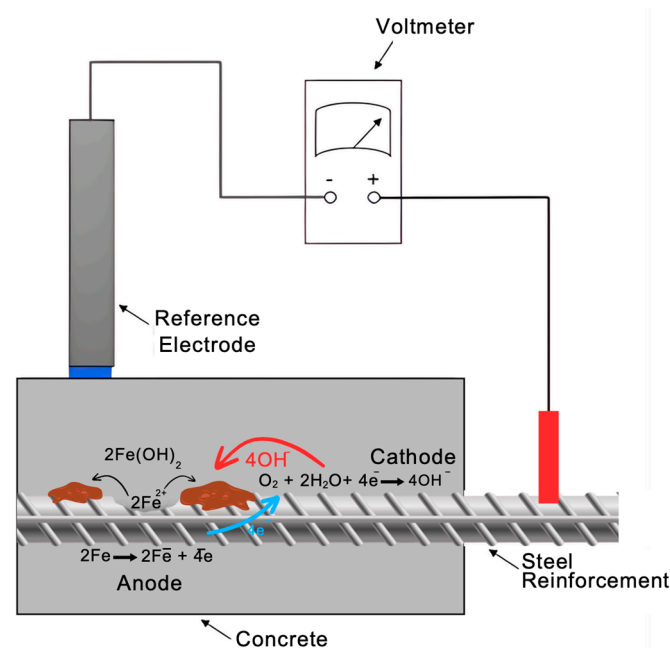


Figure 1. Integrated Diagram of Steel Corrosion Reactions and HCP Measurement Setup.

This measurement shows how the rebar's electrochemical state is, which helps figure out how likely it is to corrode [13]. For accurate readings, there must be good electrical continuity, low-resistance contact, and concrete resistivity [14]. The HCP data are examined based on defined criteria, as outlined in Table 1, which displays the corrosion probability and analysis for different potential levels [15].

Table 1. The ASTM C876 thresholds for interpreting HCP readings [15].

Half-Cell Potential with Cu/CuSO ₄ Electrode (E) [mV]	Corrosion Probability	Interpretation
More negative than −350 mV	>90% probability of active corrosion	Indicates a high likelihood of active corrosion.
Between −200 mV and −350 mV	Intermediate probability	Corrosion potential is uncertain and require further assessment.
More positive than −200 mV	<10% probability of active corrosion	Suggests a very low likelihood of active corrosion.

However, some studies warn against relying solely on HCP because it can change with changes in moisture, temperature, carbonation, and differences in the concrete matrix [16–18]. HCP measurement needs a thorough understanding of a number of important factors, such as moisture content, temperature, concrete composition, steel type, chloride concentration, and other outside factors [16,19].

Even though we know more about how corrosion affects bond strength, there is still a big gap in finding a definite link between HCP measurement and the loss of bond strength. HCP is a good way to check for corrosion and find places that are likely to corrode, but it has not been tested very well for detecting bond strength loss [20,21]. Destructive experimental techniques, including pull-out tests, have been utilized to evaluate bond strength in compromised concrete, whereas numerical simulations can emulate corrosion effects based on electrochemical principles [22–24].

Addressing this gap is essential for enhancing the predictive value of HCP as a practical tool for structural assessment [25]. Therefore, this study investigates the relationship

between HCP measurements and the degradation of bond strength in corroded reinforced concrete through combined experimental testing and numerical simulation. The study's specific objectives are as follows: (1) to simulate using COMSOL Multiphysics v6.2 the impact of corrosion on the steel-concrete interface, emphasizing bond degradation and corrosion-induced damage; (2) to examine experimental results measuring corrosion levels obtained through HCP taken with PROCEQ Profometer and pull-out tests for assessing bond strength; and (3) to assess HCP measurements in predicting bond strength degradation in concrete structures by creating a semi-empirical model that links HCP values with bond strength degradation, functioning as a forecasting tool for engineers and researchers in the field.

This integrated approach aims to support early corrosion detection, improve structural health monitoring, and contribute to more sustainable management of reinforced concrete infrastructure.

2. Experimental Program

2.1. Preparation of Concrete Specimens

The experiment included 54 reinforced concrete cube specimens, each 200 mm wide and long, with rebars that were 235 mm long and 19 mm (D19) and 22 mm (D22) in diameter. To ensure a comprehensive description of the materials utilized, the mechanical properties of the reinforcing steel are presented. The D19 and D22 rebars adopted in this study conform to the requirements of the Korean Industrial Standard KS D 3504 (SD400 grade), which prescribes a minimum yield strength of 400 MPa, an ultimate tensile strength ranging from 560 to 620 MPa, and an elastic modulus of 200 GPa. The rebar was put 135 mm into the middle of each specimen, which made the working area of 4176 mm² for D19 and 4835 mm² for D22. The examples were made using wooden forms that were 20 mm thick. The rebar was placed horizontally through an opening on one side of the form. Two coatings of epoxy and one layer of urethane were put on the part of the rebar that is non-contact. After that, the urethane-coated part was wrapped in polytetrafluoroethylene (PTFE) tape, and a 100 mm polyvinyl chloride (PVC) pipe was added to keep it from rusting even more.

Table 2 shows the different materials that went into making the concrete cubes used in this investigation. The mixture was used to make 36 cylindrical concrete samples, each 100 mm in diameter and 200 mm in length, so that material properties including strength and saturation curves could be tested. The specimens were shaped and kept in a controlled environment with a temperature of 20 ± 3 °C and humidity to help them dry out properly before being saturated. All specimens were tested in saturated surface-dry (SSD) conditions prior to the experimental procedures.

Table 2. Material properties of the concrete utilized in this study.

Mix	Design Strength (MPa)	w/c Ratio	Porosity * (%)	Unit Weight (kg/m ³)				
				W	C	G	S	AE
Mix 1	18	0.585	8.38	168	287	898	957	2.58
Mix 2	24	0.507	7.59	170	335	956	870	2.5
Mix 3	40	0.346	8.01	166	480	993	720	4.32

Note: W: water, C: Portland cement type I, G: gravel, S: sand, AE: high performance air-retraining agent. * Porosity is based on average results of experimental data.

2.2. Accelerated Corrosion and Steel Mass Loss Measurement

The concrete specimens underwent an impressed current procedure to induce different amounts of steel corrosion [2,26], as illustrated in Figure 2. To attain complete saturation, the specimens were immersed in a 3.0% NaCl solution for seven days, ensuring that the upper surface of each cube was entirely submerged in the solution. A stainless-steel mesh (SUS 316) was encased around the concrete's lateral surfaces to function as the cathode, while the implanted rebars served as the anodes. A DC power supply (ODA Programmable DC Power Supply, OPE-DI Series, manufactured by ODA Technologies, Seoul, Republic of Korea) provided a constant-voltage input (maximum current: 1.05 A) to the system, with the positive terminal connected to the rebar and the negative terminal connected to a current-measuring device (KEYSIGHT Truevolt digital multimeter, produced by Keysight Technologies, Santa Rosa, CA, USA). The corrosion process was monitored in real-time using LabVIEW 2016 software. The corrosion levels of the 19 mm and 22 mm rebars were categorized according to theoretical steel mass loss percentages of 0%, 5%, 10%, and 20%. When the impressed current approach was used, the specimens showed visible surface cracking. The number and width of the cracks increased as the corrosion levels rose, and corrosion products became visible as the rebar deteriorated.

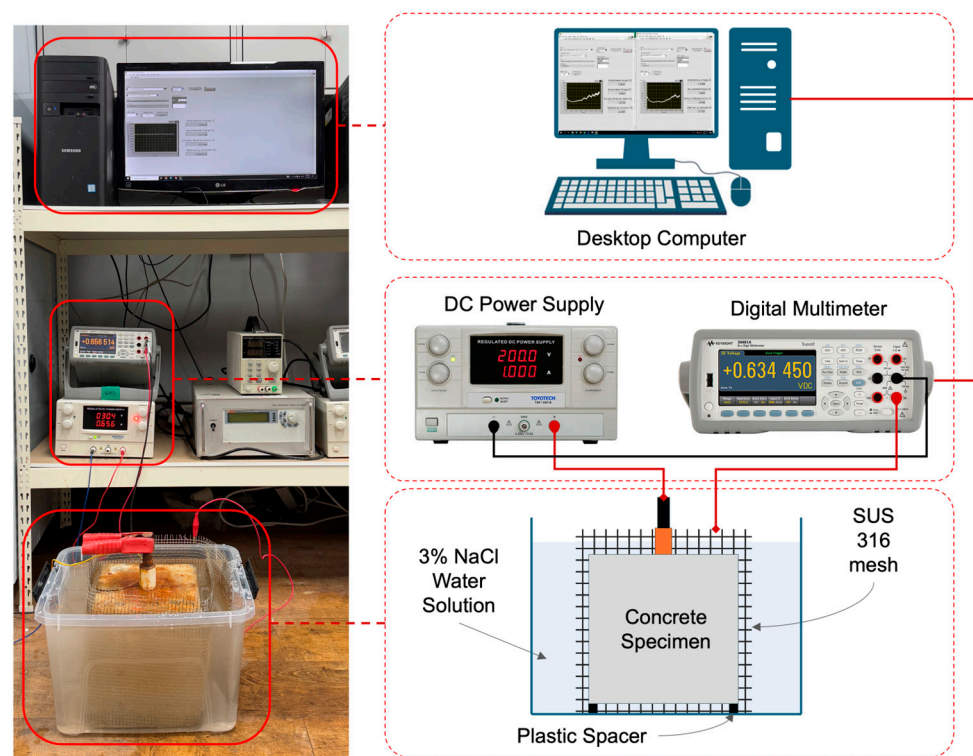


Figure 2. Experimental Setup for Accelerated Corrosion Testing of Concrete Specimens.

The amount of steel that was lost was measured using the method provided in ASTM G1 [27], "Standard Practice for Preparing, Cleaning, and Evaluating Corrosion Test Specimens." After the corroded rebars were taken out of the concrete cubes, they were cleaned with ultrasonic methods and then put in a sodium hydroxide (NaOH) solution to get rid of any corrosion byproducts. After the chemical cleaning, any leftover rust was removed by sandblasting, which used a high-pressure air jet to get rid of the rust and show the steel surface that was still intact. As shown in Figure 3, the corrosion zone of the rebar specimens in this study was confined to a 70 mm section, while the rest of the embedded steel length was protected from corrosion by epoxy coating and PVC sleeving.

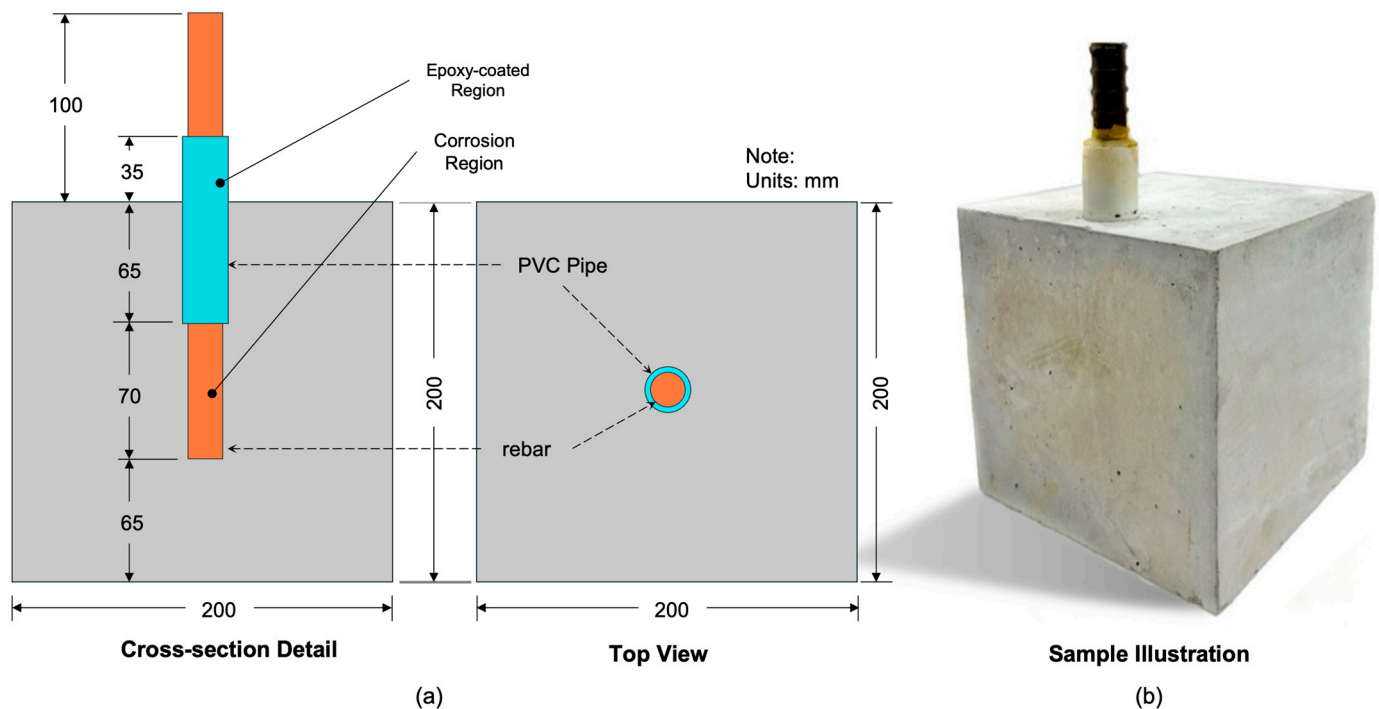


Figure 3. Preparation of concrete specimens: (a) schematic diagram of specimen configuration; (b) photograph of the original testing setup used during specimen preparation.

The steel mass loss was determined using Archimedes' principle of buoyancy. To calculate the volume of the steel corresponding to the corroded region, the rebar was submerged in water up to the 70 mm corrosion length. The volume of water displaced by the rebar was taken as the volume of the steel. From this, the mass of the steel was calculated using the known density of steel. The actual steel mass loss ratio, θ , which represents the corrosion level in this study, was then obtained by normalizing the measured mass loss from the corroded portion to the initial mass of the uncorroded rebar segment of the same length. This relationship is expressed mathematically in Equation (3):

$$\theta = \left[1 - \frac{(M_a - M_w(\theta))\rho_{\text{steel}}}{M_o\rho_{\text{water}}} \right] \times 100 [\%] \quad (3)$$

where M_a represents the mass of the rebar measured in air, $M_w(\theta)$ is the mass of the rebar partially submerged in water at the height of the working area (70 mm from the tip of the rebar), M_o is the mass of the uncorroded working area prior to the accelerated corrosion test, and ρ_{steel} and ρ_{water} are the mass densities of steel and water, respectively.

2.3. Half-Cell Potential Measurements

HCP measurements were conducted following the guidelines of ASTM C876 [28] to evaluate the electrochemical behavior of the embedded steel reinforcement at varying corrosion levels. A PROCEQ Profometer (manufactured by Proceq SA, Schwerzenbach, Switzerland), equipped with an integrated copper/copper sulfate electrode (CSE) and a high-impedance voltmeter, was used to take all measurements, as illustrated in Figure 4. Before testing, the upper smooth surface of each concrete specimen was meticulously cleaned and wet to provide optimal electrical contact between the reference electrode and the concrete. The reference electrode was positioned at a designated measurement point at the center of the 200 × 200 mm upper surface of the specimen, directly above the embedded rebar. An electrical connection with the rebar was made via a lead wire affixed to its

exposed end. The Profometer measured the difference in open-circuit voltage between the rebar and the reference electrode after making contact.



Figure 4. Image showing the experimental setup of HCP.

Before recording, the reading was allowed to stabilize, and each measurement was taken five times to get an average value. Each test was conducted using three replicate specimens, and for the HCP measurements, five readings were taken per specimen, all exhibiting a standard deviation of less than 5 mV. This reduced random fluctuations. Measurements were taken at different levels of corrosion.

2.4. Pull-Out Test and Bonding Strength Evaluation

The pull-out test, which follows the rules in ASTM C234 (Standard Test Method for Comparing Concrete Based on the Bond Developed with Reinforced Steel), was used to measure how strong the bond was between the rebar and the concrete [29]. Using this method, a specimen was made with rebar embedded in concrete. The pull-out test involved using a pull-out test apparatus to hold the rebar in place while pulling it out, as shown in Figure 5. The machine slowly increased the tensile stress until the rebar pulls out of the concrete. During the examination, the applied load, or the force required to remove the rebar from the concrete, was consistently recorded. The force was applied in incrementally, and the specimen was put under stress until it reaches failure. To find the bond strength, we divided the force exerted by the area where the rebar and concrete were bonded. The bonding area is the section of the rebar that is in contact with the concrete. Equation (4) shows the formula used to calculate the bond strength.

$$\tau = \frac{F}{\pi dl} \quad (4)$$

where τ denotes the average bonding strength and F represents the maximum pull-out force. The symbol d denotes the diameter of the steel bar, while l represents the embedment length of the steel bar. The result of this equation indicates the bond strength at the interface of the rebar and concrete, quantified in megapascals (MPa).

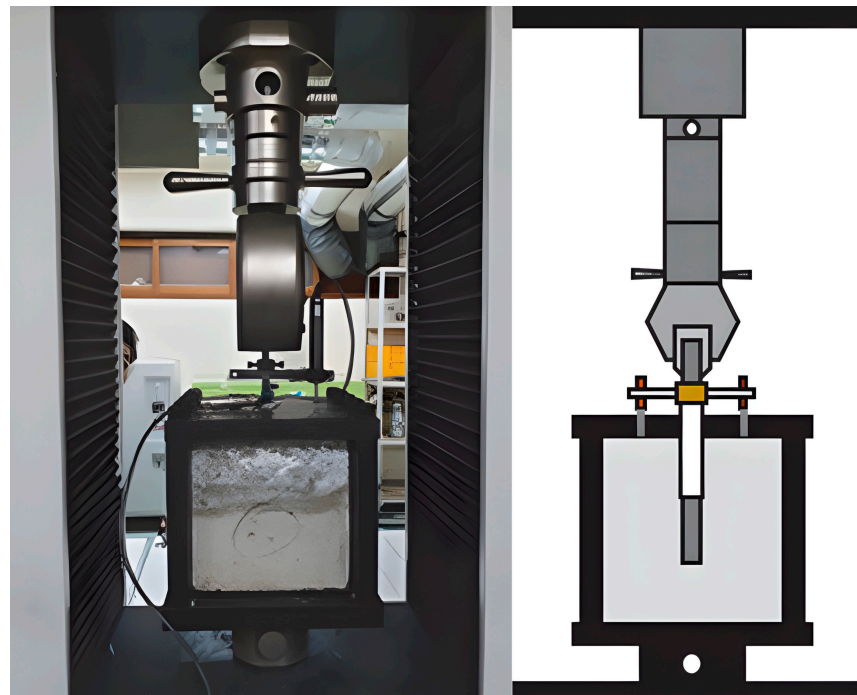


Figure 5. Image showing the experimental setup of Pull-out Test.

This procedure was necessary to find out how corrosion affected the bonding strength between the rebar and the concrete [30]. The results of the pull-out test made it possible to measure how much bond strength was lost because of corrosion. This is important for figuring out how long reinforced concrete constructions will last. The evaluation of bond strength demonstrated the influence of corroded rebar on bonding efficacy, and this data is essential for assessing the overall performance and safety of reinforced concrete elements under various conditions, especially as corrosion progresses.

3. Numerical Simulation

3.1. Principle and Physics

This study utilized numerical simulation of the Electric Currents physics interface from the AC/DC Module of COMSOL Multiphysics v6.2 [31], in alignment with the fundamental principles of Ohm's Law, as depicted by the following equation:

$$J_{\text{density}} = \sigma_{\text{el}} E_{\text{field}} + J_{\text{ext}} = -\sigma_{\text{el}} \nabla V_{\text{pot}} + J_{\text{ext}} \quad (5)$$

In this equation, σ_{el} stands the electrical conductivity, E_{field} stands for electric field, which is the same as $-\nabla V_{\text{pot}}$, (the gradient of the electric potential), and J_{ext} stands for any current density that is delivered from the outside, such as current injection or corrosion current. The charge conservation equation, commonly known as the equation of continuity, controls this. It is expressed below:

$$\nabla \cdot J_{\text{density}} = Q_j \quad (6)$$

where J_{density} is the vector for the current density and Q_j is the term for the current source. The Electric Currents interface in the AC/DC module of COMSOL Multiphysics v6.2 primarily employs Ohm's Law to simulate and analyze electric fields, currents, and potential distributions in conductive materials [32]. Ohm's Law explains how voltage, current, and resistance are related to each other. This idea says that the corrosion current density and the medium's electrical resistivity affect the voltage measured during an HCP test [33,34].

This law sets the rules for how to get HCP measurements. The continuity equation explains how electric charge is conserved. It says that any current that flows through a material must come from a source, either from within the material itself or from charge building up over time [35]. In steady-state simulations, such as the one conducted in this study, charge accumulation is assumed to be zero. The equation ensures an even distribution of current throughout the material, with the current source term specified and moving in a way that makes sense physically [36]. The electric potential distribution (V) is determined by solving the generalized continuity equation for conductive medium, integrating Ohm's Law into the continuity equation, as demonstrated in Equation (7). We used point assessments along the rebar to look at the resulting potential distribution across the concrete. This was similar to how HCP is measured in real life.

$$\nabla \cdot (-\sigma_{el} \nabla V_{pot} + J_{ext}) = Q_j \quad (7)$$

3.2. Model Geometry and Input Parameters

A two-dimensional finite element model was developed in COMSOL Multiphysics v6.2 to simulate the distribution of HCP in reinforced concrete. The numerical workflow used in constructing and solving the model is shown in Figure 6.

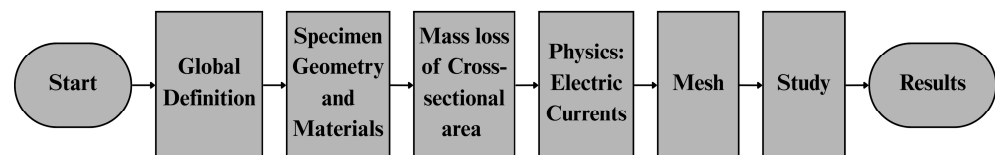


Figure 6. COMSOL Simulation Flowchart for HCP Measurement.

The overall numerical workflow shown in Figure 6 outlines the steps used to define geometry, assign material properties, impose boundary conditions, and solve the electric potential field. The model reproduced the experimental configuration, consisting of a 200 mm × 200 mm concrete domain with a centrally embedded steel rebar [2]. The Electric Currents physics interface was employed to represent the electrochemical behavior governing HCP measurements. Material properties for the concrete domain were defined using the regression-based electrical conductivity models presented in Equations (8)–(10), while the conductivity of the pore solution was fixed at 0.001 S/m. The steel rebar was modeled with high electrical conductivity to accurately represent its electrochemical response.

To properly simulate the measurement environment, appropriate boundary conditions were implemented. Current Conservation was applied throughout the concrete domain, and Electric Insulation was assigned to all exterior concrete boundaries except at the designated reference-electrode location. An Electric Potential of 0 V was imposed on this boundary to represent the copper/copper sulfate (CSE) reference electrode used in the experiment. The rebar boundary was assigned a Floating Potential condition, enabling the computation of the steel potential relative to the reference electrode, while a Normal Current Density was simultaneously applied along the rebar perimeter to simulate the anodic corrosion current. These conditions collectively captured the electrochemical potential gradients generated during corrosion.

The simulation employed a single-physics Electric Currents interface without coupling to structural or thermal fields. A physics-controlled mesh with a global element size set to fine was used across all simulation cases to resolve the steep electric potential gradients near the steel–concrete interface. Triangular second-order elements were applied, with automatic refinement concentrated around the rebar boundary. Additional nodes were generated along the steel perimeter to improve the accuracy of the computed electric

potential, ensuring stable numerical convergence and precise evaluation of the potential distribution. Regions farther from the rebar were assigned a relatively coarser discretization. Across all simulations, the mesh quality remained within acceptable numerical criteria, with average element quality values consistently exceeding 0.8.

To simulate corrosion, Normal Current Density was applied as a cathodic boundary condition along the rebar perimeter using the parameter $-J_{\text{norm}}$, where the negative value represents anodic corrosion of the steel, representing the flow of electrons away from the rebar at this boundary. The values for corrosion current density (J_c) were assigned based on data obtained from the regression analysis of the relationship between electrical resistivity and corrosion current density, as discussed below. The reference electrode was simulated by designating a 0 V electric potential condition at a certain boundary on the concrete surface, enabling the evaluation of the electric potential field in relation to this reference point. A Floating Potential condition was implemented at the rebar boundary to enable the calculation of the potential at the rebar in relation to the reference electrode. Although the electric potential of the rebar might be assessed without this condition, employing the Floating Potential improves the precision and efficacy of ascertaining the HCP values at the rebar.

The relationship between corrosion current density (J_c) and electrical conductivity (σ_{ef}) was derived from an established study that provided an empirical sixth-order polynomial correlation [37]. This correlation was derived from experimental data encompassing J_c values from 0.001 A/m² to 0.8 A/m². Equation (8) is the formulation designed to encapsulate the nonlinear relationship between pore-solution conductivity and corrosion activity. It is important to clarify that Equation (8), taken from reference [38], is applied in this study as an empirical guide to represent the general trend between corrosion current density and electrical conductivity. Although the mixture proportions in reference [38] differ from those used in this work, the simulation environment allows controlled input parameters; thus, the equation is used as a trend-based approximation rather than a mixture-specific correlation. This clarification has been incorporated to ensure transparency regarding the applicability of the model.

$$\sigma_{\text{ef}} = -6.9778 \cdot J_c^6 + 14.408 \cdot J_c^5 - 9.8241 \cdot J_c^4 + 2.3899 \cdot J_c^3 - 0.1137 \cdot J_c^2 + 0.0182 \cdot J_c + 0.0033 \quad (8)$$

The mass loss cross-sectional area of the corroded rebar significantly affects the electrical conductivity in reinforced concrete structures. As corrosion advances, the cross-sectional area of the rebar diminishes, so directly affecting the material's conductivity. A published study indicates that at 0% corrosion, the rebar maintains its complete cross-sectional area, with no water into the steel-concrete link; but, at 19.5% corrosion, the loss of area becomes significantly evident [38]. This link is important since a smaller cross-sectional area usually means a higher electrical conductivity [38–41]. The rebar's weaker structure makes it simpler for ions to pass through the concrete, which is why this happens. Furthermore, water, being conductive and a key component of corrosion, is introduced into the corroded part of the steel-concrete bond starting from corrosion levels greater than 0%, as shown in Figure 7. As a result, the water's electric conductivity is applied at all corrosion levels, further influencing the overall conductivity [42,43].

The relationship between mass loss cross-sectional area and conductivity is governed by the regression model linking corrosion current density (J_c) with electrical conductivity (σ_{ef}), as shown in Equation (8). To further quantify this effect, two additional regression models are applied. The first one correlates steel mass loss with conductivity using the equation

$$\sigma_{\text{ef}} = 0.000006x^2 + 0.00006x + 0.0036 \quad (9)$$

where x represents the percentage cross-sectional area, allowing the calculation of equivalent conductivity at various corrosion levels (0%, 2.1%, 10.1%, 14%, and 19.5%). The second equation shows how conductivity and current density are related:

$$J_c = -6815x^2 + 105.01x - 0.2707 \quad (10)$$

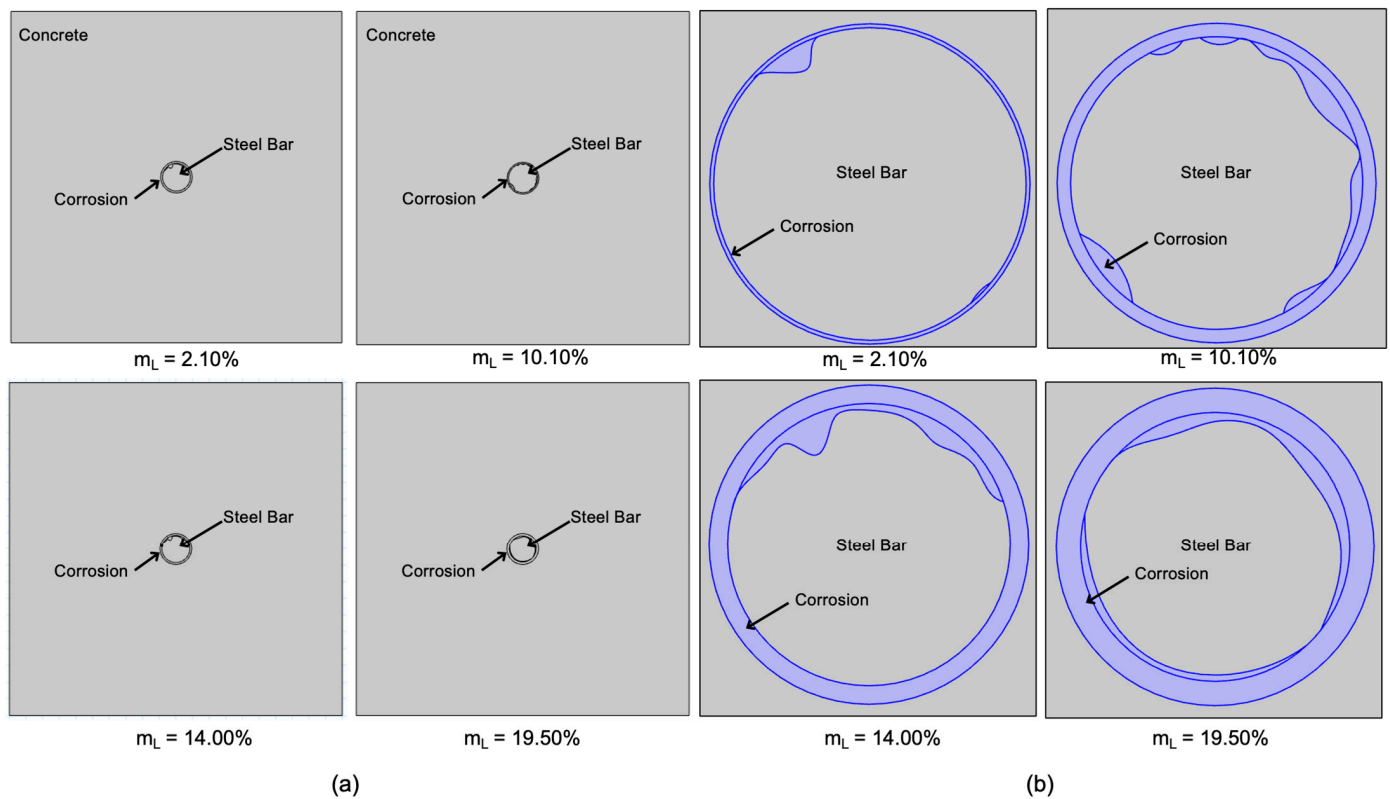


Figure 7. Cross-sectional profiles of a corroded steel bar: (a) Model of the cube; (b) the shaded area indicating the corrosion components.

This equation provides a different way to link the current density caused by corrosion to the material's electrical conductivity. Using both regression models makes it possible to calculate electrical conductivity at each level of corrosion. This helps us understand better how the loss of cross-sectional area affects conductivity at different stages of corrosion.

Related study [38] shows how the corrosion levels of 0%, 2.1%, 10.1%, 14%, and 19.5% change conductivity by making the cross-sectional area smaller. As corrosion continues, the cross-sectional area that is left gets smaller, which causes the electrical conductivity to go up, as shown by both the steel mass loss and current density models.

3.3. Half-Cell Potential and Steel Mass Loss

We figured out the electrical resistivity (ER) values from the electrical conductivity (σ_{ef}) values we got because resistivity is the opposite of conductivity. The ER data support the link between the simulated HCP distributions and the steel mass loss (m_L), that goes with them, as shown in similar studies [14,44]. The equivalent ER values associated with certain corrosion current density (J_c) circumstances were determined for each simulated scenario. After that, the relative electrical resistivity (r_e) was calculated by using Equation (11) to normalize each ER result to its starting point.

$$r_e = \frac{ER_{at \text{ specific } J_{corr}}}{ER_{initial}} \quad (11)$$

The study used a previously published paper [2] to show a relationship between electrical resistivity r_e and the actual corrosion damage, which was the loss of steel mass (m_L) in reinforced concrete samples. This reference included three separate concrete mixtures with varying mechanical and physical qualities, as shown in Table 2, to examine the impact of concrete quality on corrosion mechanisms. Figure 8 shows how r_e and m_L are linearly related for these combinations. Steel's mass loss (m_L) is shown as a linear function of r_e . We used the relative ER values from this simulation in these regression models to find the m_L values for each concrete mix.

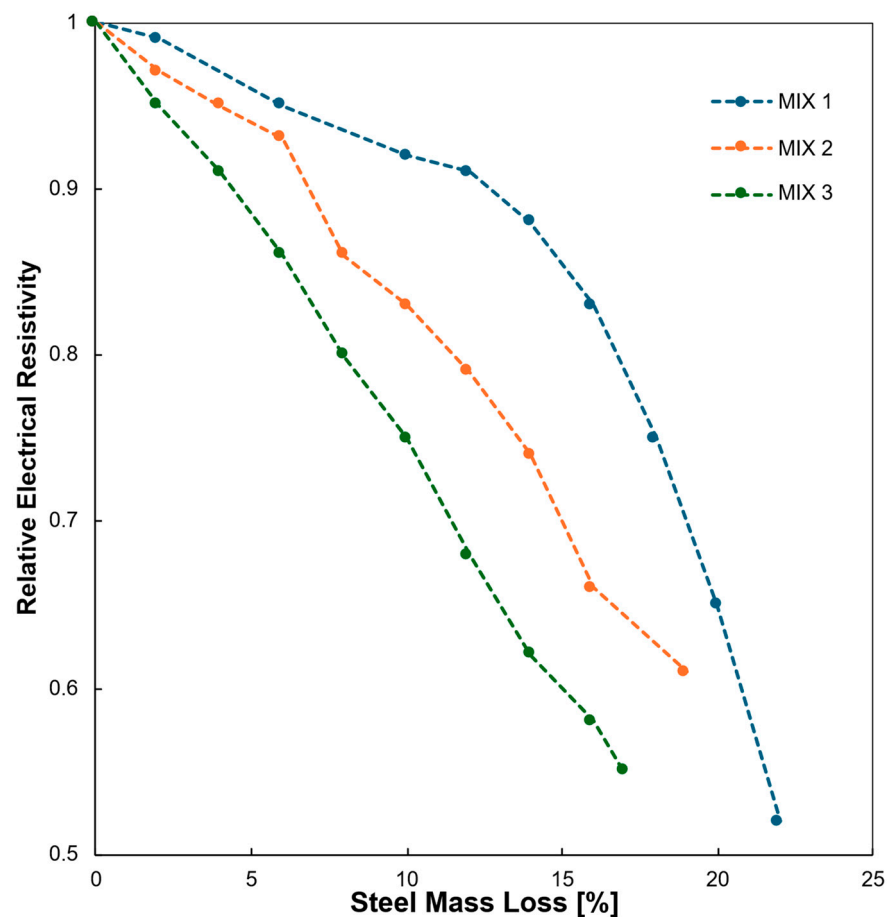


Figure 8. The correlation between relative electrical resistivity (r_e) and steel mass loss (m_L) for Mix 1, Mix 2, and Mix 3.

To integrate these findings into the numerical model, the computed m_L values were associated with the electrical conductivity (σ_{ef}) and corrosion current density (J_c) parameters defined in COMSOL. This integration links resistivity data from experiments with a conductivity model based on simulations, making it easier to build a direct quantitative correlation between HCP and mass loss. The correlation enables the numerical assessment of corrosion severity derived from the simulated electrochemical potential field.

The mass loss in cross-sectional area of steel reinforcement had a big impact on how these electrochemical parameters were figured out. As corrosion reduces cross-sectional area, the effective current density (J_c) increases because the same total corrosion current is spread out over a smaller metallic surface [38]. As J_c rises up, the electrical conductivity (σ_{ef}) also goes up, while at the same time, the resistivity (ER) of the system goes down. Changes in electrochemical parameters caused by changes in mass loss cross-section affect the HCP distribution and the ionic exchange rate inside the concrete matrix. The differences between the three concrete mixtures are due to their different material properties and the

resulting changes in J_c , σ_{ef} , and mass loss area. The analysis was confined to a relative ER value of 0.52 to ensure comparability, representing the lowest common resistivity range recorded in the reference study [2]. We used regression to look at the resulting data again to see how accurate the simulated HCP values were at predicting how bad the corrosion was in reinforced concrete.

4. Results and Discussion

4.1. Corrosion and Bonding Strength

Figure 9 clearly show how corrosion and bond strength are related for both D19 (19 mm diameter) and D22 (22 mm diameter) rebars that were put in concrete with three different mix compositions. The study aimed to investigate the impact of varying corrosion levels on bond strength, highlighting the relationship between bond strength degradation and HCP data. Mix 1, Mix 2, and Mix 3 were different concrete mixtures that varied in their water-to-cement ratio, unit weight, and admixture content, which influenced their mechanical behavior and corrosion resistance. This made the concrete weaker and more likely to rust.

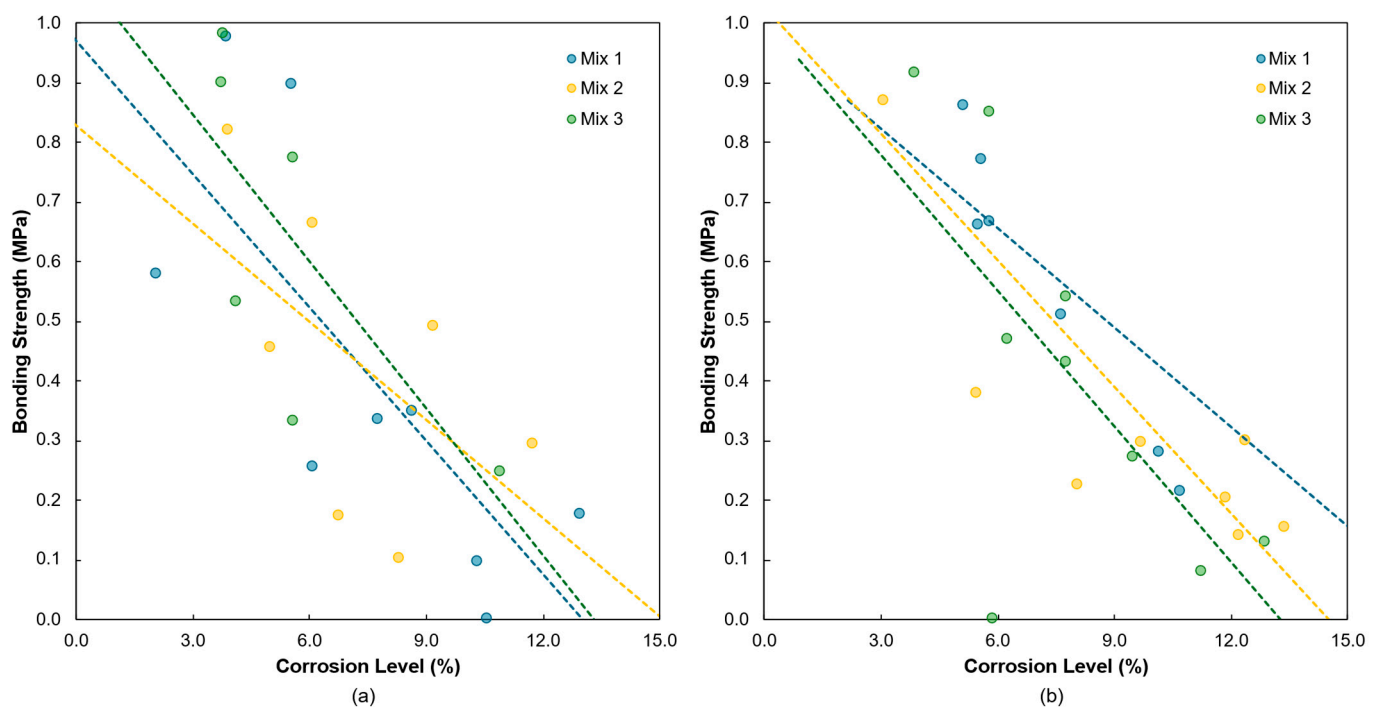


Figure 9. The correlation between relative bonding strength (MPa) and corrosion level (%) from the performed experiment involves (a) rebars measuring 235 mm in length and 19 mm in diameter (D19); (b) rebars measuring 235 mm in length and 22 mm in diameter (D22).

The experimental configuration included the accelerated corrosion of samples by an impressed current technique, followed by pull-out tests to assess bond strength. Research repeatedly demonstrates that increased corrosion levels result in weakened bond strength across all combinations and sizes of rebar. The corrosion of steel induces fractures in the surrounding concrete and compromises the bond's integrity. This is what weakens the bonding strength [21,45]. The D19 and D22 rebars revealed a comparable trend: as corrosion intensified, the bond strength decreased. D22 bars, possessing a greater cross-sectional area, exhibited a more gradual reduction in bond strength compared to D19 bars. The greater mass of steel in D22 likely enhanced its capacity to withstand pressures induced by corrosion, particularly rust growth. Both sizes of rebar exhibited a consistent pattern: as corrosion intensified, the bond strength decreased.

Destructive pull-out tests show that the bond strength is getting weaker, which shows the effects of corrosion. D22 rebars had slightly stronger bonds than D19 rebars when they were both exposed to the same amount of corrosion. This suggests that bigger diameter rebars may be more resistant to bond deterioration caused by corrosion, but they are still sensitive to long-term degradation. This study shows how important it is to take into account the size of the rebar when constructing buildings that will be exposed to corrosive conditions, since the size of the rebar may change its ability to resist corrosion over time [46–48]. In addition to the influence of rebar size, the concrete mix design also contributed to the behavior observed in this study. Mixtures with higher water–cement ratios, such as Mix 1, consistently showed lower bond strength, while mixtures with lower water–cement ratios, such as Mix 3, exhibited stronger bonding performance due to their reduced porosity and denser microstructure. However, despite these differences in bonding performance, the HCP results for the three mixes followed similar trends. Because the impressed current method imposed the same electrochemical conditions on all specimens, the HCP values did not clearly distinguish between mixtures with different water–cement ratios. To further clarify the behavior observed in Figure 9, the dispersion of bond strength results across the three concrete mixes was also analyzed. The data show moderate variability among the mixtures, with standard deviations of 0.25, 0.24, and 0.31 MPa for Mix 1, Mix 2, and Mix 3, respectively. Mix 3 exhibits the highest dispersion, indicating a wider spread of measured strengths at comparable corrosion levels and HCP values, while Mix 1 and Mix 2 display more clustered responses. This greater scatter in Mix 3 aligns with its denser microstructure and lower w/c ratio, which can heighten sensitivity to localized corrosion-induced microcracking. Overall, the observed variability remains within the typical range reported in corrosion-induced bond degradation studies and supports the reliability of the measured experimental trends.

4.2. HCP and Bonding Strength

Figure 10 illustrates the relationship between relative bonding strength (MPa) and HCP (mV) in corroded reinforced concrete rebars, as determined from pull-out tests on two types of rebars: D19 (19 mm diameter) and D22 (22 mm diameter). The data show a clear trend where, as the HCP value becomes more negative (indicating increased corrosion), the relative bonding strength decreases. This trend is consistent in both Figures 10a and 10b, though it is more pronounced for the D19 rebars.

While HCP provides a useful measure of corrosion, it is not a direct indicator of bonding strength [49,50]. The observed decrease in bonding strength with more negative HCP values suggests that corrosion weakens the bond between the concrete and the steel reinforcement. Nonetheless, the correlation is not entirely linear, particularly with the bigger D22 reinforcing bars, where the reduction in bonding strength is less evident than with the D19 reinforcing bars. The findings indicate that HCP may serve as an effective instrument for forecasting the reduction in bonding strength of corroded concrete structures. The HCP does not directly quantify bonding strength; instead, it serves as a reliable signal of corrosion, which subsequently affects the performance of the bond [20]. The correlation between HCP and bonding strength clarifies the impact of corrosion on the strength of reinforced concrete and the structural integrity.

To augment these findings, numerical models might further clarify the impact of corrosion on bonding strength, providing a more systematic and accurate prediction of how various levels of corrosion, as indicated by HCP, influence bonding strength. These simulations may assist in identifying critical HCP thresholds associated with significant bonding failures, hence enhancing the accuracy of forecasts for practical applications.

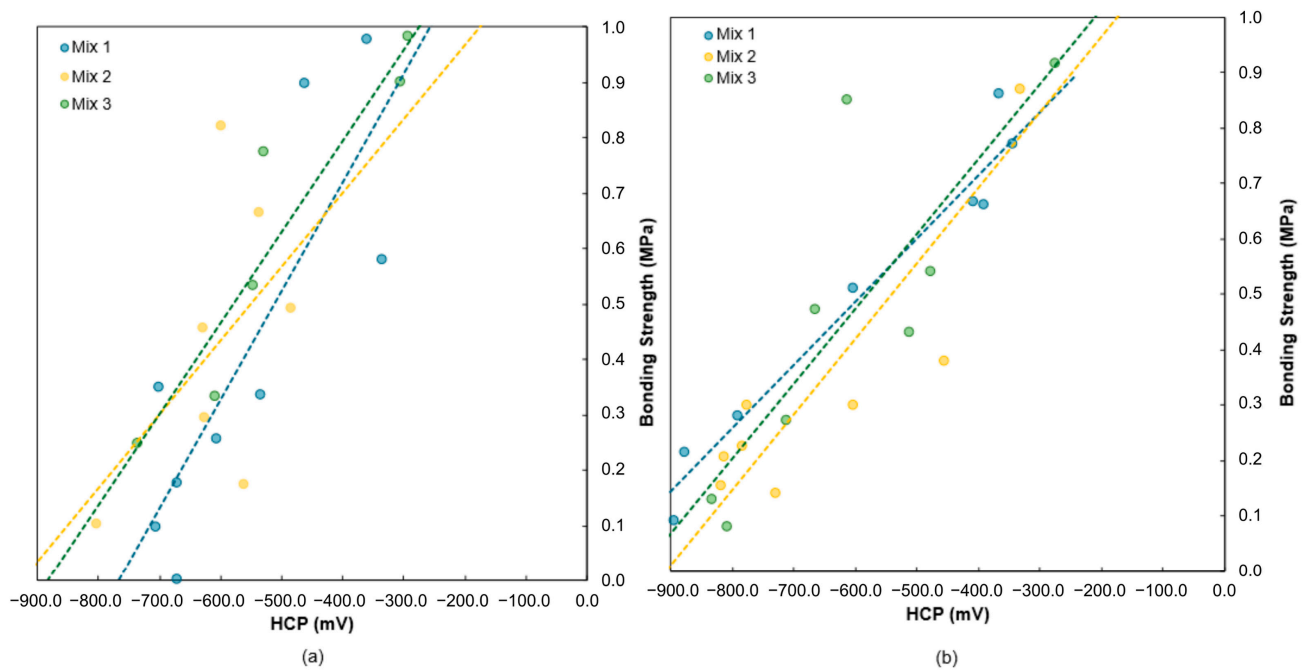


Figure 10. The relationship of relative bonding strength (MPa) and HCP (mV) from the conducted experiment (a) rebars measuring 235 in length and in diameter 19 mm (D19); (b) rebars measuring 235 in length and in diameter 22 mm (D22).

This study involves collecting data by the monitoring of HCP values to evaluate the corrosion levels of the rebars. Subsequent pull-out tests were performed to assess the comparative bonding strength of the rebars. These measurements are essential for understanding the relationship between corrosion, as indicated by HCP, and the mechanical performance of reinforced concrete, providing key information for forecasting the deterioration in bonding strength in corroded structures.

4.3. Numerical Simulation Visualization of HCP and Corroded Specimens

The numerical simulation result provides a comprehensive overview of the impact of corrosion on the distribution of HCP in reinforced concrete samples, as shown in Figure 11. As corrosion advances, the mass loss cross-sectional area of the rebar decreases, resulting in increased conductivity, as seen by elevated negative HCP values [38]. The variation in electric potential is linked with the deterioration of the bond between concrete and steel reinforcement. Corrosion compromises the connection, resulting in lowering the HCP values that makes the structure less stable. The relationship between bond strength and HCP is complex; however, it is evident that corrosion degrades the bond, hence reducing the accuracy of HCP measurements. The precise form of this relationship is dependent upon certain material qualities, including the extent of corrosion and the influence of the environment. The simulation results indicate that HCP values are reliable indicators of corrosion levels, despite not directly measuring bond strength. Corrosion is a significant factor in the degradation of bonds.

Minimal dispersion of negative potentials occurs around the rebar in the absence of corrosion. This is evidenced by the faint shades of blue surrounding the rebar. This indicates that minimal corrosion is occurring at this point. As corrosion increases to 2.1%, conductivity rises to 0.004 S/m, current density progresses to 0.028 A/m², and electric potential diminishes to −311.02 mV. This indicates that the distribution of potential has undergone an incremental change. The gradient adjacent to the rebar intensifies, transitioning from a light blue to a subtle yellow green. This indicates the start of corrosion. When corrosion reaches 10.1%, the HCP value drops to −755.33 mV. The conductivity

is 0.005 S/m, and the current density is 0.086 A/m². The electric potential distribution around the rebar has grown a lot, and the potential field has changed to a darker yellow color, which means that corrosion is happening faster. The rise in negative potentials shows that corrosion is getting worse. At 14% corrosion, the conductivity reaches 0.006 S/m, the current density rises to 0.121 A/m², and the HCP value drops to −935.89 mV. The potential field keeps becoming bigger, and the yellow lines that you can see turn red. The electric potential field has grown, which means that corrosion is getting worse and the concrete's structural integrity is getting worse. When the corrosion level reaches 19.5%, the conductivity goes up to 0.007 S/m, the current density goes up to 0.163 A/m², and the HCP value goes down to −1037.40 mV. The potential distribution has grown evenly around the rebar, and dark red regions now surround it. This indicates that corrosion activity is at its peak, with extensive negative potentials revealing significant degradation of rebar and extensive damage to the concrete. Currently, the electric potential field exhibits the highest gradients, indicating the greatest corrosion.

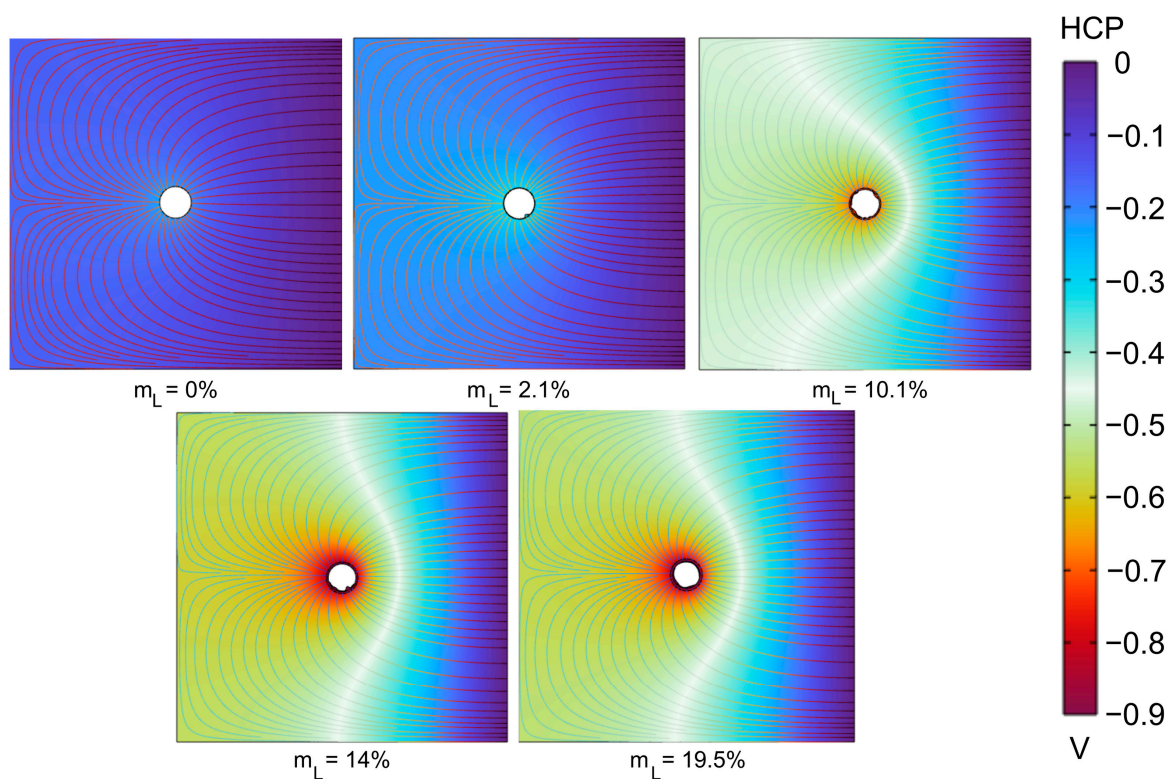


Figure 11. Electric potential distribution with increasing corrosion levels.

Figure 12 shows the relationship between mass loss cross-sectional area and HCP values. It shows that when the rebar's cross-sectional area gets smaller because of higher degrees of corrosion, conductivity goes up, and HCP observations go down. The electric potential value becomes more negative as the corrosion percentage rises from 0% to 19.5%. This shows that the corrosion is getting worse [51]. The HCP value is −219.44 mV at 0% corrosion, which means there is very little corrosion. However, at 19.5% corrosion, the value drops to −1037.40 mV, which means there is a lot of corrosion.

This simulation and visualization illustrate the impact of corrosion on the distribution of electric potential in reinforced concrete. As corrosion progresses, the electric potential distribution surrounding the rebar transitions from a uniform low-potential field to an extensive high-potential field, impacting a broader area of the concrete. The colors that appear on the probable distribution map, transitioning from blue to yellow to red, indicate the severity of corrosion. The red dots indicate the areas of greatest corrosion. This image

illustrates the mechanism of corrosion and assists in identifying the concrete components that are prone to failure due to this process. This enables us to come up with early and more efficient methods for concrete maintenance.

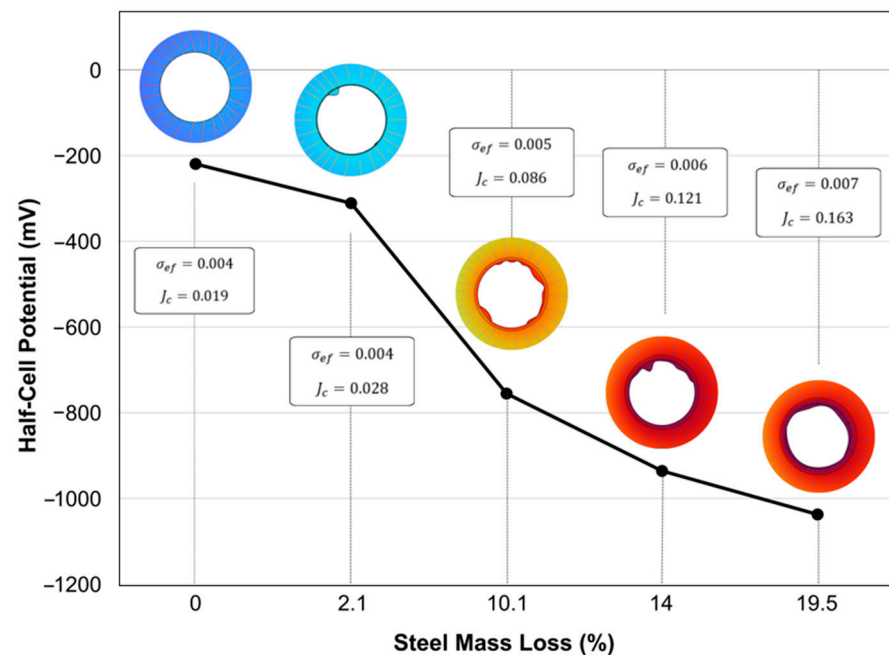


Figure 12. Effect of Mass Loss Cross-Sectional Area on Half-Cell Potential.

4.4. Summary and Practical Applications

This paper investigated the relationship between HCP measurements and loss of bond strength in corroded reinforced concrete through experiment and numerical simulation. Experimental evidence has indicated corrosion dramatically lowers the bond between steel reinforcement and concrete. Moreover, a reduction in bond strength was observed with increasing levels of corrosion especially when corrosion was caused by an impressed current method. Pull-out tests showed that bond strength decreases with increased corrosion affecting structural integrity. This was observed in all the rebar sizes: the bigger rebars (D22) deteriorated at a slower rate compared to the smaller rebars (D19). The rebar diameter is important in determining the strength of bond against corrosion. Thus, in both types of experiments, there was a negative correlation between bond strength and the severity of corrosion, which was also evident.

HCP measurements were effective to measure the level of corrosion. As corrosion deepened, HCP values moved further into the negative indicating deepening active corrosion. The HCP was associated with a decrease in bond strength, but not linearly. Therefore, HCP can be used to estimate the severity of corrosion, but it cannot be used to directly estimate bond strength. Moreover, these are laboratory specimen results which are preliminary. The size of the sample was limited, and the conditions were controlled. Electrical interactions at the concrete-steel interface were simulated numerically in COMSOL Multiphysics and it was not easy to predict electric current behavior and environmental factors on the corrosion rate. The simulations were model-steady and might not represent dynamic corrosion in the real world completely.

The integration of simulation and experiment can provide useful information, but existing models require improvement. Hence, the dynamic variables that need to be included in future work which incorporates temperature variations, humidity variations, or other environmental factors that influence corrosion. Having real materials and field conditions will enhance the accuracy of the model. Integrating HCP data with bond

strength data may provide more powerful predictive maintenance system capabilities, which would assist in tracking and treating concrete structures. Additionally, HCP can alert engineers to early corrosion, and this will allow engineers to strategize on how to repair and reduce expenses. Given that, further research ought to collect additional data and develop models to cover other complicated and real life.

Subsequent studies have to also integrate HCP with Electrical Resistivity (ER) to allow more precise predictions of steel mass-loss. HCP represents the electrochemical state of the steel, whereas ER demonstrates the ionic movement in concrete that is critical in the research of corrosion dynamics [52–54]. By integrating these non-destructive practices in one model, there will be a reduction in uncertainty, enhancement in reliability, and adjustment to dynamic environmental factors. Additionally, such an interdisciplinary methodology would enable the development of deterioration maps with clear boundaries and facilitate the use of machine-learning technologies to track things in real-time. Additionally, the study acknowledges that SEM–EDS microstructural analysis could not be performed because all tested specimens had already been disposed of after the experimental program. This limitation has been noted, as such analysis would have allowed direct confirmation of the corrosion products observed.

Several limitations of the present setup should also be recognized. The impressed current method, although efficient for accelerating corrosion, does not fully replicate natural corrosion processes and may affect the uniformity of corrosion development. Furthermore, all experiments were conducted under controlled laboratory conditions, which do not reflect the effects of environmental variations such as fluctuating moisture, temperature, and chloride exposure. The absence of microstructural verification further constrains the interpretation of the corrosion mechanisms. These limitations have been explicitly acknowledged to provide appropriate context for interpreting the study's findings.

Table 3 illustrates the relationship between HCP values and the decline in bond strength. Reduced HCP values are used to express quicker corrosion and reduced bonds between steel and concrete. This classification can be used to predict changes in bond strength and proactive maintenance decisions to make by engineers. It is an important solution when it comes to determining structural integrity and deciding on repair prioritization.

Table 3. Preliminary classification of HCP and Bond Strength Degradation (%) quantified.

HCP	Bond Strength Degradation (%)	Description
≤ -200 mV	~0–5%	Negligible corrosion
$-200 \text{ mV} < x < -350$ mV	~5–20%	Moderate corrosion
≥ -350 mV	~20–50%	Severe corrosion

5. Conclusions

The aim of this study was to establish a relationship between damage caused by corrosion and degradation of bond strength of reinforced concrete. Through measuring HCP and comparing it with bond strength, we established that bond strength is reduced with the advancement of corrosion, particularly in smaller rebars (D19). HCP was found to be an effective measure of the degree of corrosion. Even though there was no accurate measure of the strength of the bonds, the results indicated that there was a strong correlation between HCP values and bond degradation.

COMSOL Multiphysics was used to model a numerical simulation of the corroded steel in concrete, and it provided much information on the behavior of corroded steel. Simulations were also found to be consistent with experimental results, which confirmed the presence of a definite correlation between HCP, level of corrosion and the impact of the remaining cross-sectional area on the conductivity as well as the distribution of HCP.

Furthermore, this study introduces a preliminary classification of HCP ranges associated with bond-strength degradation, providing a practical framework for predicting corrosion-related deterioration in reinforced concrete. This approach supports enhanced monitoring and more informed maintenance planning. To improve the applicability of the model under real-world conditions, future work should incorporate dynamic environmental factors such as variations in moisture and temperature. It is also recommended that subsequent studies calibrate simulation inputs using experimental data obtained from specimens with identical mixture conditions, thereby enabling the development of mixture-specific relationships between corrosion current density and electrical conductivity for greater model precision. In addition, future investigations should examine the direct influence of the water–cement ratio on HCP behavior by testing mixes with controlled w/c variations under natural corrosion exposure rather than impressed current corrosion. Finally, incorporating SEM–EDS microstructural characterization in future research is encouraged to verify the corrosion products and to strengthen the correspondence between experimental findings and numerical simulations, following approaches presented in recent studies [55,56].

Subsequent research should prioritize the augmentation of the dataset and the incorporation of environmental variables to enhance the precision of numerical models, facilitating improved long-term forecasts and more effective infrastructure maintenance.

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