

Article

The Effect of Electrolyte Composition on the Corrosion Protection Performance of PANI and PANI/CeO₂ Composite Coatings

Lin Zhang ¹, Haoyao Zhou ², Yu Chen ^{2,3,*}, Zhongnian Yang ⁴ and Lu Zhang ^{1,*}

¹ Key Laboratory of the Ministry of Education for Advanced Catalysis Materials, College of Chemistry and Materials Science, Zhejiang Normal University, Jinhua 321004, China

² School of Materials and Energy, Foshan University, Foshan 528000, China

³ School of Intelligent Manufacturing, Zhejiang Guangsha Vocational and Technical University of Construction, Jinhua 322100, China

⁴ College of Chemical Engineering and Materials, Shandong University of Aeronautics, Binzhou 256600, China

* Correspondence: 20263111@zjgsdx.edu.cn (Y.C.); zhanglu@zjnu.edu.cn (L.Z.)

Abstract

The electrolytic composition plays an important role in the structure and corrosion protection performance of electro-polymerized coating. In the present work, oxalic acid, hydrochloric acid, sulfuric acid, phosphoric acid and benzoic acid were utilized as electrodeposition electrolytes to prepare a PANI coating. The PANI coating deposited in benzoic acid showed a compact and uniform structure with an adhesion grade of 0. Electrochemical tests revealed that the benzoic acid-doped PANI coating exhibited the smallest value of corrosion current density of $2.571 \mu\text{A}\cdot\text{cm}^{-2}$ and the largest inhibition efficiency of 92.6% among the investigated acidic electrolytes. Moreover, the influence of co-electrodeposition conditions, including cerium nitrate concentration, ammonium acetate concentration and electrolyte pH value on the corrosion protection performance of co-electrodeposited PANI/CeO₂ was investigated and the optimal co-electrodeposition condition was found to be 0.3 mol/L aniline, 0.04 mol/L benzoic acid, 0.10 mol/L cerium nitrate, 0.10 mol/L ammonium acetate and pH of 5.5, under which condition the corrosion current density was decreased to $0.199 \mu\text{A}\cdot\text{cm}^{-2}$ and the inhibition efficiency reached 99.4%.

Keywords: polyaniline; electrolyte composition; CeO₂; corrosion



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1. Introduction

Due to the outstanding electrochemical and electrical/electronic capabilities and good mechanical and thermal stability, conductive polymers have attracted great attention in recent years, which have a widespread application in many areas, such as energy storage [1,2], flexible electronics [3,4], supercapacitor [5,6], electrochemical sensors [7], corrosion protection [8–10], and so on. Among the developed conducting polymers, the polyaniline (PANI) and PANI-based materials have been the most widely investigated, owing to their facile synthesis, low cost and good environment stability [11]. In the field of corrosion protection, PANI has been utilized as an efficient corrosion inhibitor because soluble PANI can adsorb on the metal substrate surface to inhibit the corrosion rate through the functional group C=N in the PANI molecules [12]. Another popular usage of PANI is as a coating filler [13,14]. For example, Chen [15] dispersed perfluorooctanoic acid-adopted PANI nanoparticles into epoxy coating for enhanced anti-corrosion. The prepared

perfluorooctanoic acid-adopted PANI nanoparticles exhibited excellent hydrophobicity and dispersibility. The impedance modulus of the fabricated composite coating at 0.01 Hz was higher than $6 \times 10^8 \Omega \cdot \text{cm}^2$ after 9 days. Liu [16] introduced plate-like structure PANI in the waterborne epoxy matrix. The well-dispersed PANI plate significantly improved the anti-corrosion performance and the impedance modulus of this coating was over $109 \Omega \cdot \text{cm}^2$ after corrosion in a 3.5 wt.% NaCl solution for 40 days. Gao [17] compared the corrosion performance of epoxy coatings in the absence and presence of PANI nanowires in neutral salt, alkaline and acidic aqueous solution. The enhanced corrosion protection property of PANI/epoxy coatings was assigned to the passivation capability and physical barrier effect of PANI nanowires. Another important use of PANI is as protective coatings [9,18–20]. The supporting electrolytes for electro-polymerizing PANI coating influence significantly the structure and corrosion protection ability of the obtained layer. Krajić [21] electro-synthesized polyaniline coatings using sulfuric acid and phosphoric acids. The PANI layer deposited in a phosphate electrolyte showed better protective property than that in a sulfuric acid solution. Moradi [22] deposited series of PANI films doped with CH_3COO^- , HSO_4^- , NO_3^- , H_2PO_4^- , and NaSO_4^- on the 304 SS substrate. Experimental and theoretical tests revealed that the PANI coating doped with CH_3COO^- presented the most durable anti-corrosion performance, which charge transfer resistance increased 100-fold after corrosion 20 days in the 3.5 wt.% NaCl solution. Till now, owing to the complicated corrosion systems (different corrosive solutions, different preparation methods, different electro-polymerization conditions), the impact of electrolyte composition on the protective property of electro-polymerized PANI coating for mild steel substrate in NaCl solution is still controversial and needs a systematical investigation.

In recent years, CeO_2 has been utilized as a promising corrosion-protective species and exhibits good self-healing capability [23–25]. For example, Han [26] studied the corrosion behavior of epoxy resin coating loading CeO_2 and benzotriazole. The optimal protective performance was supplied by the composite coating containing 0.3% CeO_2 and 20% BTA. The strengthened corrosion protection ability was originated from the barrier effect of CeO_2 particles and chemical inhibition of BTA molecules. Chen [27] prepared a BTSPA/ CeO_2 composite film to prevent carbon steel from corrosion in an alkaline NaCl solution. The polarization resistance of this hybrid was about seven times larger than that of the control. Some researchers have reported the corrosion protection performance of PANI coating by implanting CeO_2 particles [28,29]. The added CeO_2 particles on the one hand acted as additives to fill the holes or cracks of organic coatings, and on the other hand served as corrosion inhibitors. Alsaad [30] constructed a hydrophilic PANI/ CeO_2 nanocomposite film by introducing CeO_2 nanoparticles into the PANI matrix. The composite film showed a high protection efficiency of 92.25% for carbon steel in 3.5 wt.% NaCl solution. However, the directly added CeO_2 particles may aggregate in the organic coating, which subsequently cannot achieve its best protection performance. Sasikumar [29] synthesized a PANI/ CeO_2 nanocomposite (PCN) to protect mild steel against corrosion in 0.5 M HCl solution. The fabricated PCN acted as a mixed-type inhibitor and showed an inhibition efficiency of 69.25%. The low inhibition efficiency may be originated from a relatively weak adhesion. Although the loading of CeO_2 particles into PANI film has been investigated and an enhanced corrosion protection performance was evaluated, the co-electrodeposition of PANI/ CeO_2 composite coating using a proper electrolyte containing aniline monomer and Ce^{3+} using in situ electrodeposition method has rarely been reported.

In our previous work, we reported a PANI/ CeO_2 composite coating by in situ electrochemical method [31]. However, the impact of the electrodeposition electrolyte on the composite coating structure and anti-corrosion performance has not been systematically studied and optimized. In this study, the effect of different acidic electrolytes on the

structure and anti-corrosion property of electrodeposited PANI film was initially studied. Then the superior acid electrolyte was utilized to prepare the PANI/CeO₂ composite coating by introducing Ce³⁺ in the electrolyte solution. Furthermore, the influence of co-electrodeposition conditions, including cerium nitrate concentration, ammonium acetate concentration and electrolyte pH value on the corrosion protection performance was investigated and the optimal co-electrodeposition condition was successfully obtained.

2. Experiments

2.1. Materials

The mild steel substrate was purchased from Changzhou Shengtak Seamless Steel Tube Co., Ltd. (Changzhou, China). Aniline ($\geq 99.5\%$), cerium nitrate (99.95%) and ethanol were obtained from Shanghai Macklin Biochemical Technology CO., Ltd. (Shanghai, China). Oxalic acid (98%), benzoic acid ($\geq 99.5\%$), sulfuric acid (95.0~98.0%), hydrochloric acid (36.0~38.0%), phosphoric acid ($\geq 85.0\%$) and ammonium acetate ($\geq 98.0\%$) were purchased from Sinopharm Chemical Reagent Co., Ltd. (Shanghai, China). All chemicals were used without further purification.

2.2. Electro-Polymerization of PANI and PANI/CeO₂ Coatings

The electro-polymerization was performed on a Shanghai Chenhua CHI660A electrochemical workstation (Shanghai, China) using a classic three-electrode system, where mild steel samples, a saturated calomel electrode (SCE) and a large platinum sheet were served as the working electrode, reference electrode and counter electrode, respectively. The mild steel samples were abraded with different grades of silicon carbide (SiC) paper from 600# to 2000#, washed with ethanol several times and at last dried in air. In a typical electro-polymerization, the solution composed of 0.3 mol/L aniline and 0.3 mol/L oxalic acid were employed as the electrodeposition electrolyte and the pH was adjusted to 5.0. The coatings were electro-polymerized using a cyclic voltammetry (CV) technique between -0.5 and 1.6 V (vs. SCE) at a scan rate of 20 mV/s, and the cycle number is 10. Different kinds of acids, including hydrochloric acid, sulfuric acid, phosphoric acid, benzoic acid were utilized to electrodeposit PANI coating. In the case of preparing PANI/CeO₂ composite coating, the electrolyte was changed to a mixed solution containing acid, cerium nitrate and ammonium acetate. The electrochemical deposition condition was the same as that of synthesizing pure PANI coating.

2.3. Structure Characterization and Corrosion Tests

The thickness of prepared pure PANI coating and PANI/CeO₂ composite coating was measured using a Dektak 150 profilometer (Veeco, Germany) and found to be approximately 28.5 and 32.8 μm , respectively. The surface morphology of prepared PANI coatings using different electrolytes was characterized using a Hitachi SU-8010 scanning electron microscopy (SEM). The adhesion of the coatings was tested according to the ISO 2409 standard [32]. The corrosive medium of 3.5 wt.% NaCl solution was prepared by diluting a proper amount of NaCl in deionized water. The open circuit potential (OCP), electrochemical impedance spectroscopy (EIS) and Tafel polarization curves were carried out to evaluate the corrosion protection performance of synthesized PANI and PANI/CeO₂ composite coatings. The EIS was conducted at the open circuit potential (E_{ocp}) in the frequency range from 10^5 kHz to 10^{-2} Hz with an AC amplitude of 20 mV. The experimental EIS data was fitted using Z-view 3.3 software. The Tafel polarization curves were recorded in the potential range from $E_{\text{ocp}} - 250$ mV to $E_{\text{ocp}} + 250$ mV with a scanning rate of 0.1 mV/s. All the electrochemical measurements were repeated three times to ensure reliability.

3. Results and Discussion

3.1. The Effect of Acid Composition on the Physicochemical Properties of PANI Coating

The effect of acid composition on the physicochemical properties of electro-polymerized PANI coatings is summarized in Table 1. It can be seen that during the polymerization of PANI coating using hydrochloric acid electrolyte, the pitting simultaneously occurs on the mild steel substrate which significantly destroys the isolation structure of the electro-polymerized PANI coating between the substrate and the corrosive medium, leading to a weak adhesion of grade 2. When electro-polymerized in a phosphoric acid, a uniform and light green PANI coating was successfully prepared, but it fails to provide sufficient adhesion and the synthesized coating easily detaches from the mild steel substrate in large pieces even with a gentle rinse using deionized water. Therefore, the utilization of hydrochloric acid and phosphoric acid as ideal electrolytes for PANI electro-polymerization is ruled out. Although the sulfuric acid medium is also prone to produce minor corrosion of mild steel substrate, a lower concentration promotes the formation of a relatively well-adhered and dense PANI coating. In comparison, the electrolytes of oxalic acid and benzoic acid facilitate a compact and uniform PANI coating on mild steel substrate.

Table 1. The effect of acid composition on the physicochemical properties of electro-polymerized PANI coatings.

Electrolyte Composition	Concentration (M)	Coating Appearance	Surface Appearance	Adhesion (Grade)
oxalic acid	0.3	green, uniform	no visible corrosion	0
hydrochloric acid	0.1	green, uneven	pitting corrosion	2
sulfuric acid	0.2	green, uniform	pitting corrosion	0
phosphoric acid	0.1	light green, uniform	no visible corrosion	3
benzoic acid	0.04	dark green, uniform	no visible corrosion	0

Figure 1 displays the surface morphologies of prepared PANI coatings from different acid compositions. In the case of oxalic acid electrolyte, the PANI coating presents relatively smooth morphologies with few small particles on the surface. When utilizing hydrochloric acid electrolyte, some holes and defects appear on the coating surface, which may be related to the simultaneous strong acid attack on the mild steel substrate during the electro-polymerizing PANI coating process. The same phenomenon was also observed when employing sulfuric acid electrolyte. This loose and porous structure will inevitably weaken the corrosion protection property of the fabricated PANI coating. For phosphoric acid electrolyte, few aggregates can be detected to form an uneven morphology. Conversely, the deposited PANI coating in benzoic acid electrolyte exhibits uniform and dense structure, which is helpful to better protect the mild steel substrate.

Figure 2 depicts the EIS plots of blank mild steel and the PANI coatings prepared in oxalic acid, sulfuric acid and benzoic acid in 3.5 wt.% NaCl solution. It can be seen from the Nyquist diagram that the constructed PANI coating doped with oxalic acid exhibited an almost overlapped arc with that of the bare sample. The PANI coating deposited in benzoic acid electrolyte possessed a significantly larger radius of the semicircle than that in the sulfuric acid media. This result suggests that the PANI coating synthesized in benzoic acid electrolyte has the largest corrosion resistance and the corrosion of mild steel substrate in NaCl solution is markedly suppressed. Additionally, two capacitive loops at high and middle frequencies were observed for the prepared PANI coatings from different acidic electrolytes, which was assigned to the charge transfer process and PANI coating capacitance, respectively [33]. Meanwhile, only one time constant appeared for bare mild steel sample in the middle frequency region, which was due to the charge transfer process

during mild steel corrosion. As a result, two different types of electric equivalent circuits, as presented in Figure 3, were performed to analyze the EIS data. The fitted results are listed in Table 2. The polarization resistance R_p is defined as the sum of the charge transfer resistance (R_{ct}) and coating resistance (R_c), which was utilized to calculate the corrosion protection efficiency (PE%) of electro-polymerized PANI coatings in different acidic electrolytes from the following equation [34].

$$R_p = R_{ct} + R_c \quad (1)$$

$$PE(\%) = 1 - \frac{R_p^{bare}}{R_p^c} \quad (2)$$

where R_p^{bare} and R_p^c represent the polarization resistance of bare mild steel and PANI coated samples, respectively. The calculated values of PE% are also listed in Table 2.

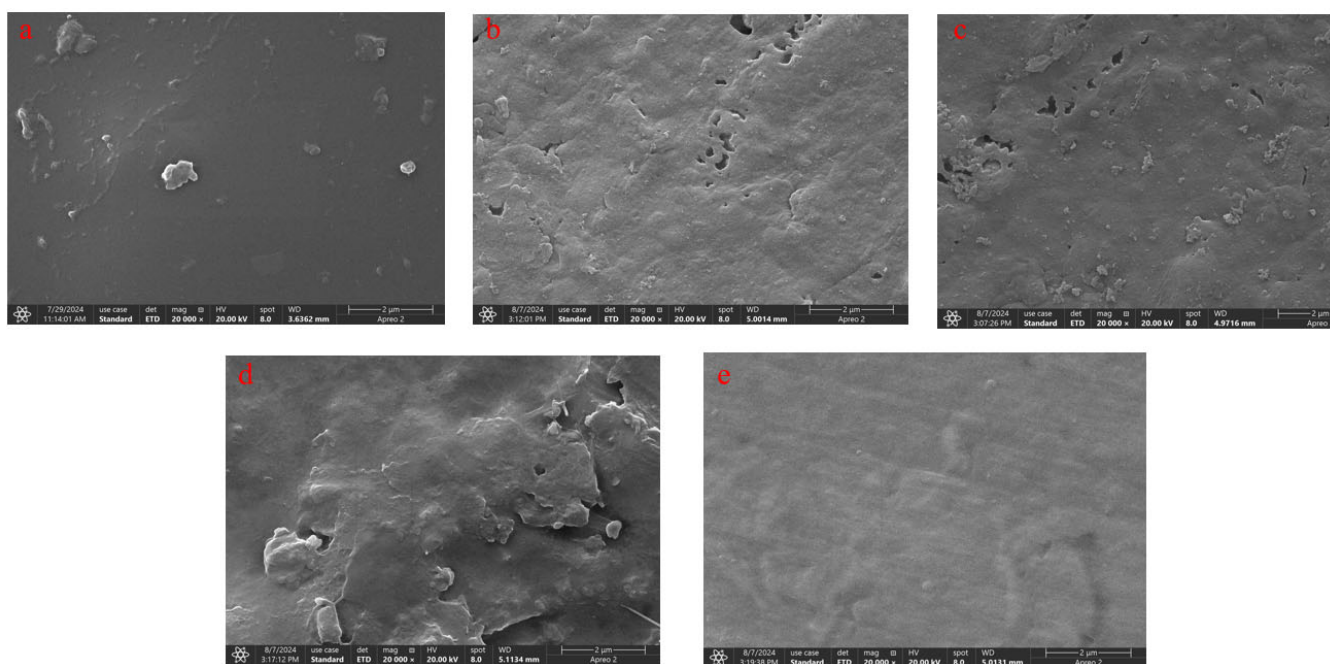


Figure 1. Surface morphologies of prepared PANI coatings from (a) oxalic acid, (b) hydrochloric acid, (c) sulfuric acid, (d) phosphoric acid, and (e) benzoic acid.

Table 2. EIS fitting results for blank mild steel and the PANI coatings prepared in oxalic acid, sulfuric acid and benzoic acid in 3.5 wt.% NaCl solution.

Sample	R_c ($\Omega \cdot \text{cm}^2$)	CPE_c ($\Omega^{-1} \cdot \text{cm}^{-2} \cdot \text{s}^n$)	n_f	R_{ct} ($\Omega \cdot \text{cm}^2$)	CPE_{dl} ($\Omega^{-1} \cdot \text{cm}^{-2} \cdot \text{s}^n$)	n_d	χ^2 10^{-3}	R_p ($\Omega \cdot \text{cm}^2$)	PE%
blank	-	-	-	1.06×10^3	3.81×10^{-5}	0.832	0.89	1.06×10^3	-
oxalic acid	25.1	6.86×10^{-4}	0.704	1.14×10^3	3.17×10^{-5}	0.865	1.64	1.17×10^3	9.40
sulfuric acid	43.8	1.19×10^{-5}	0.733	7.23×10^3	7.54×10^{-6}	0.813	1.15	7.27×10^3	85.4
benzoic acid	67.4	8.37×10^{-6}	0.750	8.47×10^3	6.26×10^{-6}	0.756	1.52	8.54×10^3	87.6

The PANI coating-covered samples showed larger values of charge transfer resistance in comparison with the bare mild steel, suggesting the restrained corrosion rate of mild steel substrate in NaCl solution by the deposited PANI coatings. The protection efficiency was calculated to be 9.40% for oxalic acid, for which a small value has also been observed by other researchers [35,36]. Notably, the PANI coating doped with benzoic acid exhibits the largest R_p value, which is indicative of superior anti-corrosion performance and consequently possesses the largest PE% of 87.6%. Obviously, the values of double-layer capacitance present a downward trend: bare mild steel substrate ($3.81 \times 10^{-5} \Omega^{-1} \cdot \text{cm}^{-2} \cdot \text{s}^n$)

> oxalic acid ($3.17 \times 10^{-5} \Omega^{-1} \cdot \text{cm}^{-2} \cdot \text{s}^n$) > sulfuric acid ($7.54 \Omega^{-1} \cdot \text{cm}^{-2} \cdot \text{s}^n$) > benzoic acid ($6.26 \Omega^{-1} \cdot \text{cm}^{-2} \cdot \text{s}^n$). It is reported that a smaller value of CPE_{dl} usually corresponds to a smaller corrosion area with a constant thickness [37]. Therefore, the smallest value of CPE_{dl} further verifies the enhanced corrosion protection capability of the PANI coating prepared from benzoic acid electrolyte.

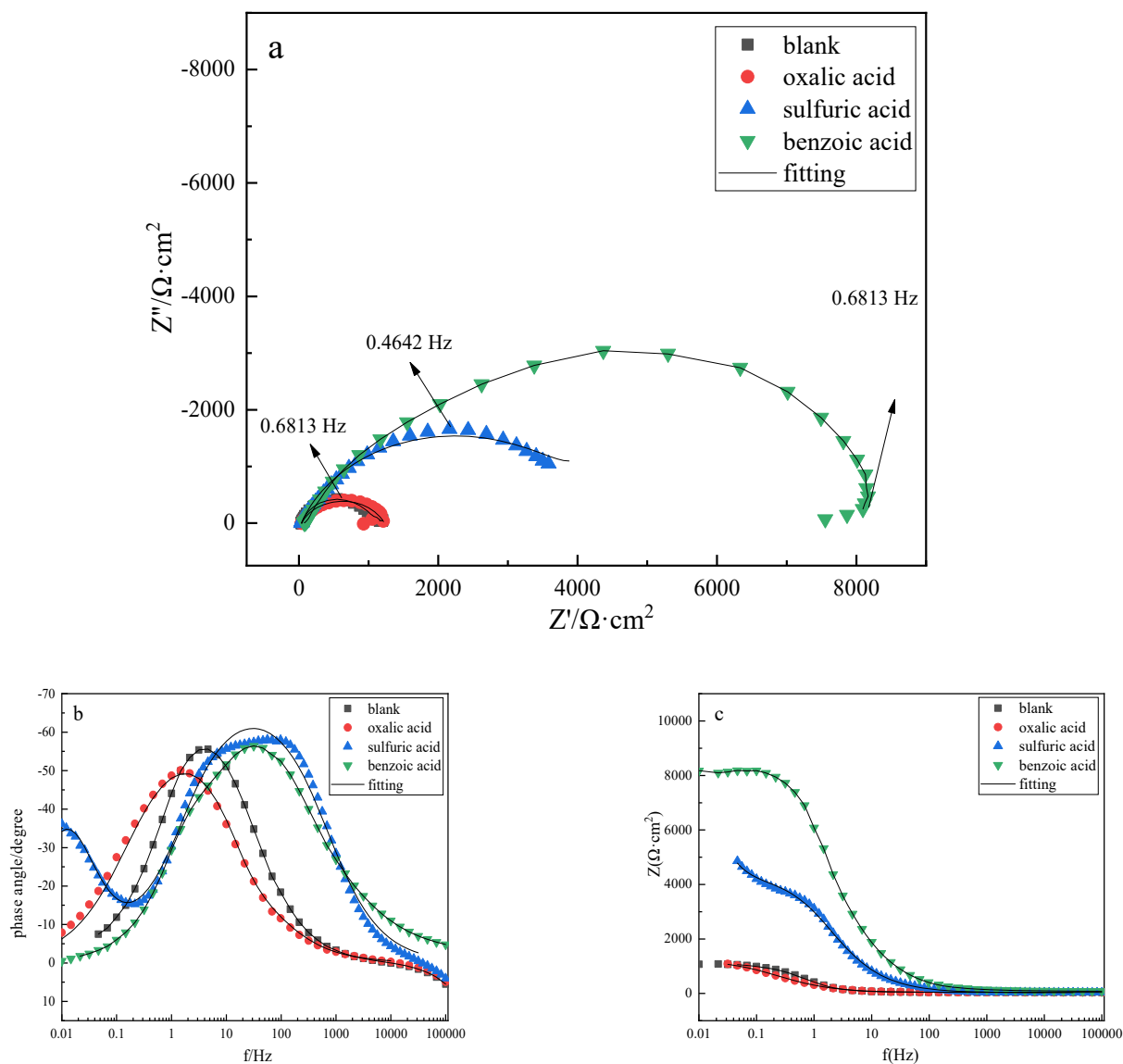


Figure 2. (a) Nyquist diagram and (b,c) Bode diagram of blank mild steel and the PANI coatings prepared in oxalic acid, sulfuric acid and benzoic acid in 3.5 wt.% NaCl solution.

Figure 4 displays the polarization curves of blank mild steel and PANI coatings prepared in oxalic acid, sulfuric acid and benzoic acid electrolytes in 3.5 wt.% NaCl solution. It is apparent that the corrosion potential shifts positively in the presence of PANI coatings on mild steel substrate. Both the anodic and cathodic parts were influenced by the electrodeposited pure PANI coating. The informative electrochemical parameters, including corrosion potential (E_{corr}), corrosion current density (I_{corr}) and anodic and cathodic slopes (β_a and β_c) were obtained from an extrapolation method and the results are presented in Table 3. In addition, the inhibition efficiency of the fabricated coatings was calculated as follows [38],

$$\text{IE}(\%) = 1 - I_{\text{corr}}^{\text{coated}} / I_{\text{corr}}^{\text{bare}} \quad (3)$$

where I_{corr}^c and I_{corr}^{bare} correspond to the corrosion current density of bare mild steel and PANI coated samples, respectively. The calculated values of IE% were also summarized in Table 3. As seen, the E_{corr} of blank mild steel and PANI coatings prepared in oxalic acid, sulfuric acid and benzoic acid electrolytes were -0.923 , -0.776 , -0.569 and -0.681 V, respectively. The corrosion potential of the electro-polymerized PANI coatings moves in the positive direction compared to the control, which matches with the OCP tests. The PANI coating deposited in benzoic acid electrolyte shows the smallest value of I_{corr} and the largest inhibition efficiency of 92.6%, indicating the best anti-corrosion ability among the tested acidic electrolytes. It is notable that the calculated inhibition efficiency from EIS tests is different from that by polarization curves. That is because EIS test was performed under weak polarization with just 20 mV potential amplitude, while polarization curves were recorded in a wider potential range. Based on the above analysis, benzoic acid was utilized as the superior electrolyte for electro-polymerization of PANI composite coating in the following study.

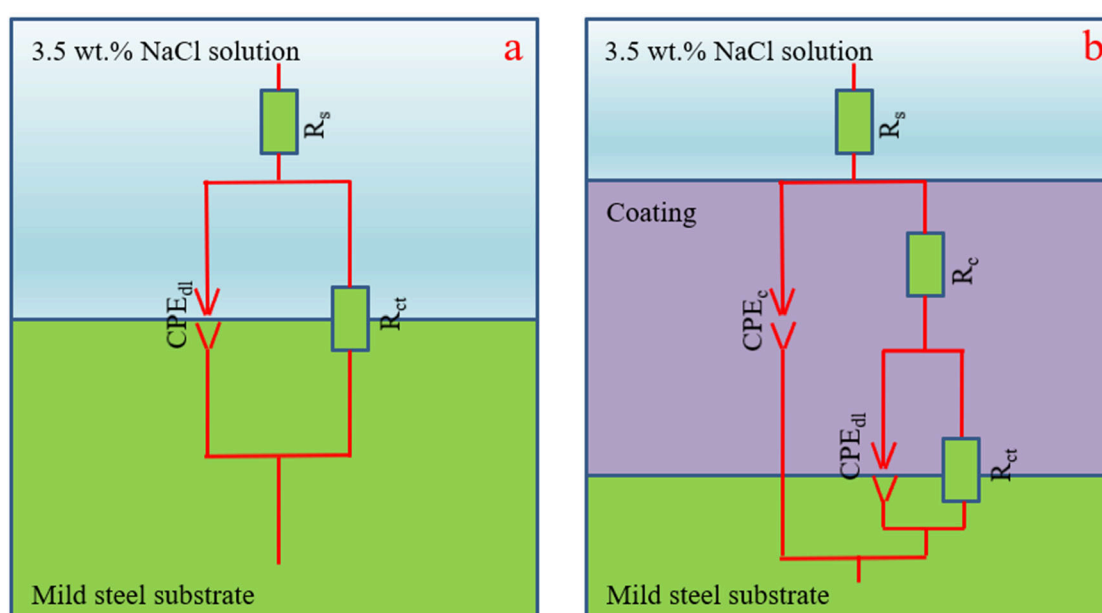


Figure 3. Electric equivalent circuits for fitting the EIS data of blank (a), and PANI coatings (b). (R_s : solution resistance; R_{ct} : charge transfer resistance; CPE_{dl} : double-layer capacitance; CPE_c : coating capacitance; R_c : coating resistance).

The open circuit potential (E_{ocp}) of blank mild steel and the electro-polymerized PANI coatings prepared in oxalic acid, sulfuric acid and benzoic acid electrolytes in 3.5 wt.% NaCl solution is shown in Figure 5. Apparently, the E_{ocp} of the blank sample decreases gradually during the whole immersion period, which may be attributed to the dissolution process of the oxide film on the mild steel surface [39]. After electro-polymerizing PANI coating, the E_{ocp} initially decreases and then reaches a relatively stable value after immersion about 2500 s. The initial reduction is owing to the permeation of corrosive species through the microdefects into the substrate/coating interface. Meanwhile, the blank sample showed the most negative E_{ocp} value at around -0.751 V after immersion 1 h. When covered by PANI coatings, the E_{ocp} moved positively to the passive region. As also shown in Table 3, the mild steel substrate presents a more positive corrosion potential than that of the control. This phenomenon has also been reported by other researchers and explained by the anodic corrosion mechanism of PANI coating [40,41]. It is worth noting that the sample doped with benzoic acid presented the largest E_{ocp} value of approximately -0.625 V.

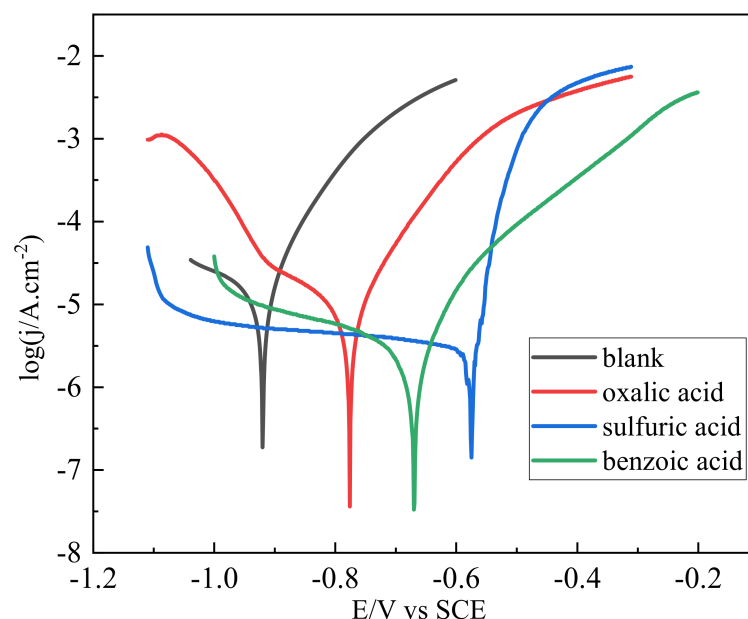


Figure 4. Polarization curves of blank mild steel and PANI coatings prepared in oxalic acid, sulfuric acid and benzoic acid electrolytes in 3.5 wt.% NaCl solution.

Table 3. Potentiodynamic polarization parameters for blank mild steel and the PANI coatings prepared in oxalic acid, sulfuric acid and benzoic acid in 3.5 wt.% NaCl solution.

Sample	E_{corr} (V)	I_{corr} ($\mu\text{A}\cdot\text{cm}^{-2}$)	$-\beta_c$ ($\text{mV}\cdot\text{dec}^{-1}$)	β_a ($\text{mV}\cdot\text{dec}^{-1}$)	IE%
blank	-0.923 ± 0.028	34.62 ± 1.05	193 ± 7.3	78 ± 3.4	-
oxalic acid	-0.776 ± 0.015	5.344 ± 0.14	182 ± 4.8	161 ± 5.5	84.6
sulfuric acid	-0.569 ± 0.018	3.219 ± 0.12	416 ± 9.5	69 ± 2.6	90.7
benzoic acid	-0.678 ± 0.021	2.571 ± 0.07	265 ± 5.2	187 ± 5.2	92.6

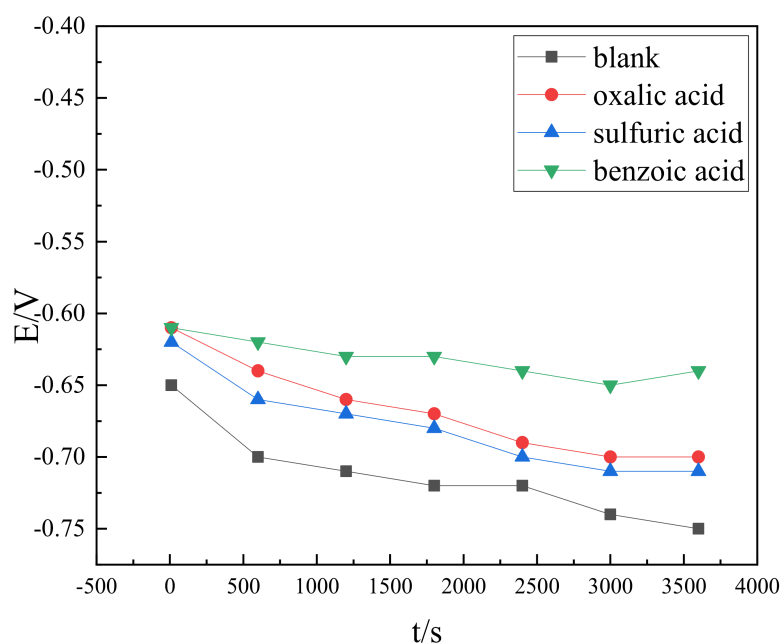


Figure 5. Open circuit potential of blank mild steel and the electro-polymerized PANI coatings prepared from oxalic acid, sulfuric acid and benzoic acid electrolytes in 3.5 wt.% NaCl solution.

3.2. The Effect of Electrolyte Composition on the Corrosion Protection Properties of PANI/CeO₂ Composite Coating

The electrolyte composition, including cerium nitrate concentration, ammonium acetate concentration and electrolyte pH value, plays an important role in the corrosion protection performance of co-electrodeposited PANI/CeO₂ composite coating. According to the above results, benzoic acid was applied in the composite electrolyte for co-electrodeposition of PANI/CeO₂ composite coating. Therefore, different conditions to electro-polymerize PANI/CeO₂ composite coating, as shown in Table 4, were systematically investigated.

Table 4. Electrolyte composition for co-electrodeposition of PANI/CeO₂ composite coatings.

No	Cerium Nitrate (M)	Ammonium Acetate (M)	pH
1	0.05	0.10	5.5
2	0.10	0.10	5.5
3	0.15	0.10	5.5
4	0.10	0.05	5.5
5	0.10	0.15	5.5
6	0.10	0.10	5.0
7	0.10	0.10	6.0

3.2.1. Cerium Nitrate Concentration

Figure 6 shows the open circuit potential of PANI/CeO₂ composite coatings co-electrodeposited at different concentrations of cerium nitrate in 3.5 wt.% NaCl solution. PANI/CeO₂ (0.10 M cerium nitrate) presented the highest potential, about -0.525 V, followed by PANI/CeO₂ (0.15 M cerium nitrate) at about -0.538 V, and PANI/CeO₂ (0.05 M cerium nitrate) at approximately -0.563 V, with the lowest potential. The PANI/CeO₂ composite coating deposited in the electrolyte containing 0.10 M cerium nitrate exhibited the most positive value of E_{ocp} , which demonstrates the strongest stability against corrosion.

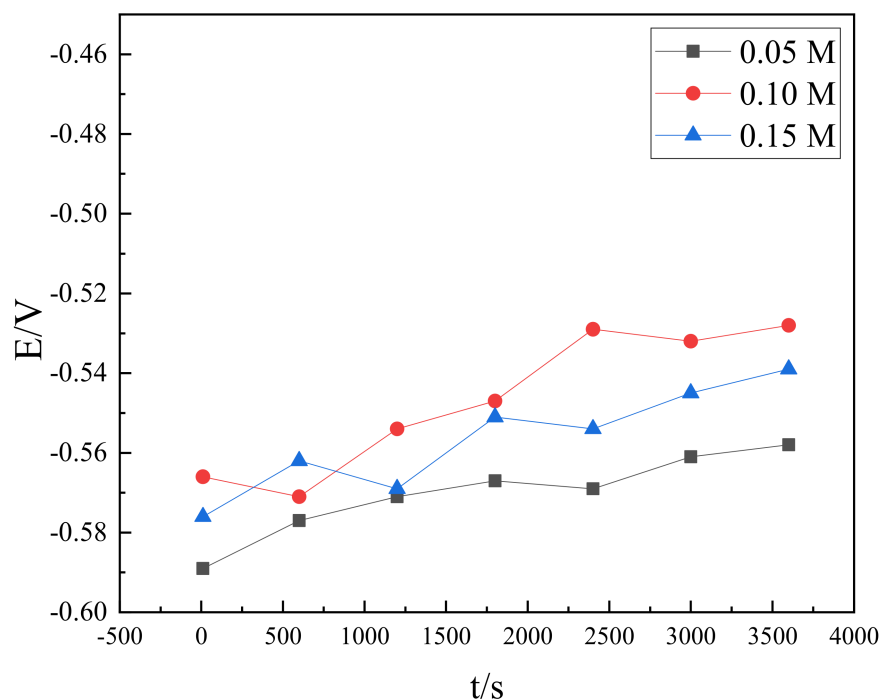


Figure 6. Open circuit potential of PANI/CeO₂ composite coatings prepared at different concentrations of cerium nitrate in 3.5 wt.% NaCl solution.

Figure 7 depicts the EIS result of PANI/CeO₂ composite coatings prepared at different concentrations of cerium nitrate in 3.5 wt.% NaCl solution. It is well accepted that the impedance modulus ($Z_{0.01\text{Hz}}$) at 0.01 Hz was effective to assert the corrosion protection performance of a coating [42]. Based on the Bode plots in Figure 7, PANI/CeO₂ (0.10 M cerium nitrate) has the largest $Z_{0.01\text{Hz}}$ value of 22.07 k $\Omega\cdot\text{cm}^2$, while PANI/CeO₂ (0.05 M cerium nitrate) has the lowest $Z_{0.01\text{Hz}}$ value of 11.04 k $\Omega\cdot\text{cm}^2$, indicating a relatively good and poor corrosion resistance, respectively. These values are much larger than that of the bare mild steel substrate (1.08 k $\Omega\cdot\text{cm}^2$) and pure PANI coating (8.17 k $\Omega\cdot\text{cm}^2$), revealing that the co-electrodeposited CeO₂ particles markedly improve the anti-corrosion ability of pure PANI coating. It is interesting that the frequency corresponding to the phase angle peak follows the trend: PANI/CeO₂ (0.10 M cerium nitrate) < PANI/CeO₂ (0.15 M cerium nitrate) < PANI/CeO₂ (0.05 M cerium nitrate), which suggests that the co-electro-polymerized PANI/CeO₂ composite coating prepared from 0.10 M cerium nitrate electrolyte possesses the slowest corrosion rate. The electric equivalent circuits, as shown in Figure 4, were also utilized to fit the experimental EIS data and the obtained electrochemical parameters are summarized in Table 5. The synthesized PANI/CeO₂ composite coating prepared from 0.10 M cerium nitrate exhibits the largest value of R_p and consequently the highest PE of 98.3%.

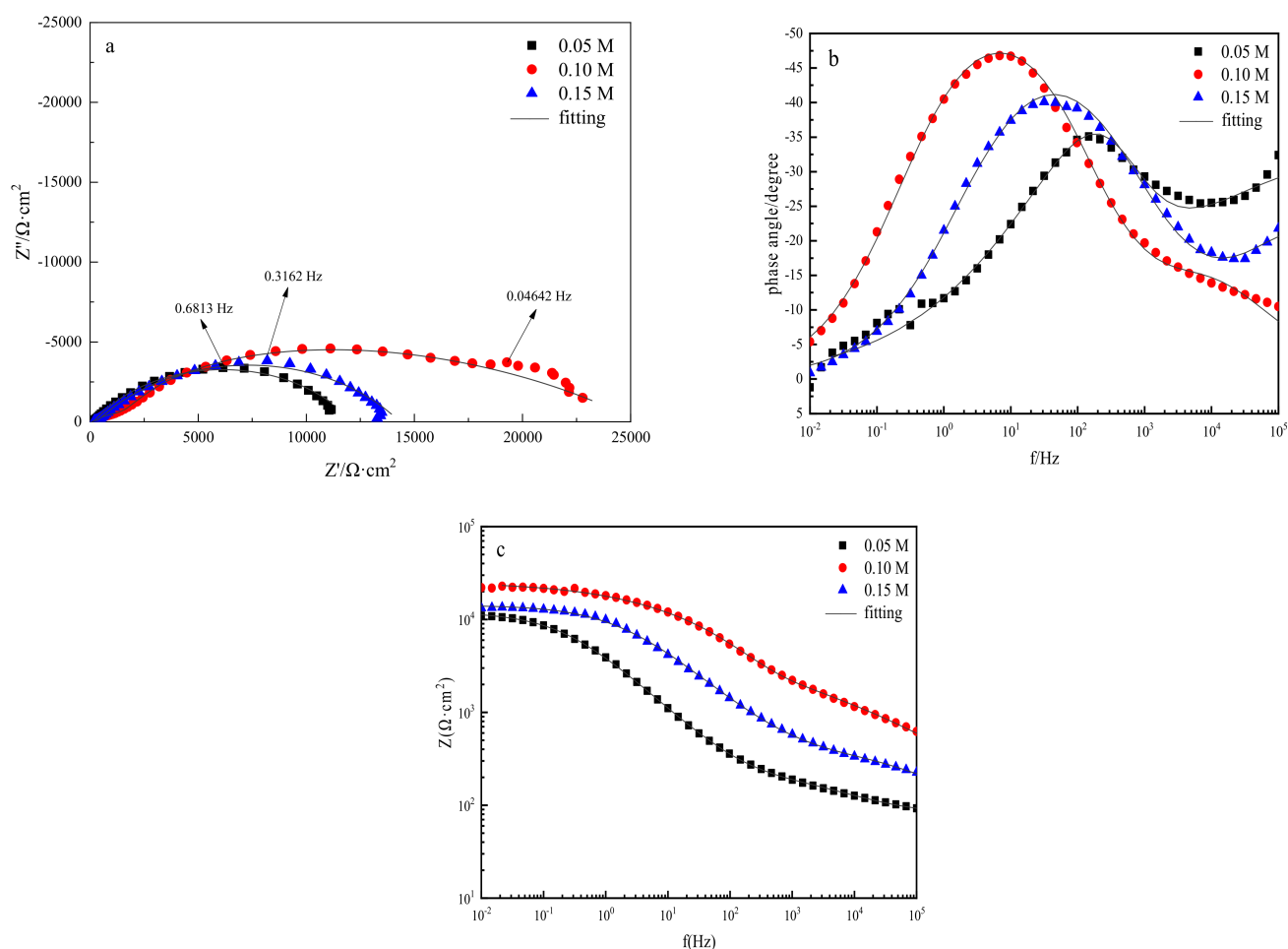
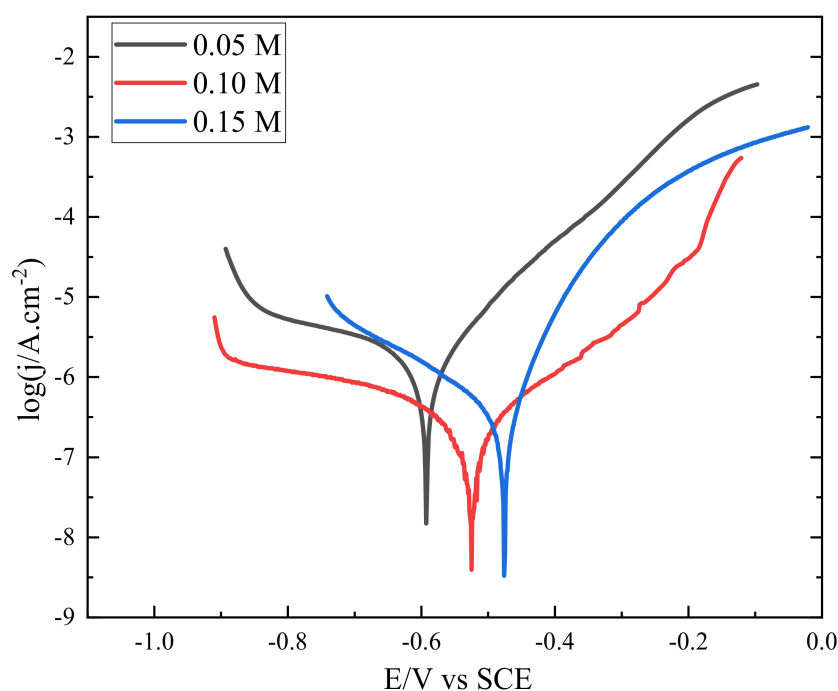


Figure 7. (a) Nyquist, (b,c) Bode plots of PANI/CeO₂ composite coatings prepared at different concentrations of cerium nitrate in 3.5 wt.% NaCl solution.

Table 5. EIS fitting results for PANI/CeO₂ composite coatings prepared at different concentrations of cerium nitrate in 3.5 wt.% NaCl solution.

Concentration (M)	R_{ct} $k\Omega \cdot cm^2$	CPE_{dl} $\Omega^{-1} \cdot cm^{-2} \cdot s^n$	n_c	R_c $\Omega \cdot cm^2$	CPE_c $\Omega^{-1} \cdot cm^{-2} \cdot s^n$	n_{dl}	χ^2 10^{-3}	R_p $k\Omega \cdot cm^2$	PE%
0.05 M	20.65	4.83×10^{-6}	0.813	131.9	1.74×10^{-5}	0.857	1.68	20.78	94.9
0.10 M	55.78	7.79×10^{-7}	0.899	4934	2.41×10^{-6}	0.842	1.25	60.71	98.3
0.15 M	26.91	1.07×10^{-6}	0.847	810.6	5.13×10^{-6}	0.844	1.47	27.72	96.2

Figure 8 presents the potentiodynamic polarization curves of PANI/CeO₂ composite coatings prepared at different concentrations of cerium nitrate in 3.5 wt.% NaCl solution. The calculated electrochemical parameters are listed in Table 6. The corrosion potential of all the samples shifts to a positive value in comparison to the blank (−0.923 V) and pure PANI coating (−0.678 V), revealing the enhanced anti-corrosion property. In addition, the fabricated PANI/CeO₂ composite coating deposited in the electrolyte containing 0.10 M cerium nitrate shows the smallest corrosion current density of $0.199 \mu A \cdot cm^{-2}$ and a corresponding largest inhibition efficiency of 99.4%, which agrees well with the EIS measurements.

**Figure 8.** Potentiodynamic polarization curves of PANI/CeO₂ composite coatings prepared at different concentrations of cerium nitrate in 3.5 wt.% NaCl solution.**Table 6.** Potentiodynamic polarization parameters of PANI/CeO₂ composite coatings prepared at different concentrations of cerium nitrate in 3.5 wt.% NaCl solution.

Concentration (M)	E_{corr} (V)	I_{corr} ($\mu A \cdot cm^{-2}$)	$-\beta_c$ ($mV \cdot dec^{-1}$)	β_a ($mV \cdot dec^{-1}$)	IE%
0.05	-0.598 ± 0.021	2.57 ± 0.08	338 ± 6.3	158 ± 5.1	92.6
0.10	-0.524 ± 0.013	0.199 ± 0.007	324 ± 7.2	173 ± 4.9	99.4
0.15	-0.487 ± 0.015	1.380 ± 0.04	267 ± 6.5	116 ± 3.2	96.0

3.2.2. Ammonium Acetate Concentration

The influence of ammonium acetate concentration on the corrosion protection property of PANI/CeO₂ composite coating was conducted at a constant cerium nitrate concentration

of 0.10 M and electrolyte pH of 5.5. The open circuit potential of PANI/CeO₂ composite coatings prepared at different concentrations of ammonium acetate in 3.5 wt.% NaCl solution is shown in Figure 9. The E_{ocp} of all these specimen moves gradually in the positive direction during the initial immersion period, which may be related to the passivation effect of the covered coating. After 2500 s, the E_{ocp} reaches a stable value. Figure 10 presents the EIS results of PANI/CeO₂ composite coatings prepared at different concentrations of ammonium acetate in 3.5 wt.% NaCl solution. It can be seen that the PANI/CeO₂ hybrid deposited in the electrolyte containing a 0.10 M ammonium acetate exhibits the largest diameter of the capacitive loops. On the other hand, this composite also possesses the largest impedance modulus, suggesting a superior anti-corrosion ability. The fitted results, as listed in Table 7, indicate that the values of R_{ct} present a downward trend: PANI/CeO₂ (0.10 M ammonium acetate) > PANI/CeO₂ (0.15 M ammonium acetate) > PANI/CeO₂ (0.05 M ammonium acetate). The opposite variation trend was detected for double-layer capacitance (CPE_{dl}), further confirming the significantly strengthened corrosion resistance of the PANI/CeO₂ composite that co-electrodeposited in the electrolyte containing 0.10 M ammonium acetate.

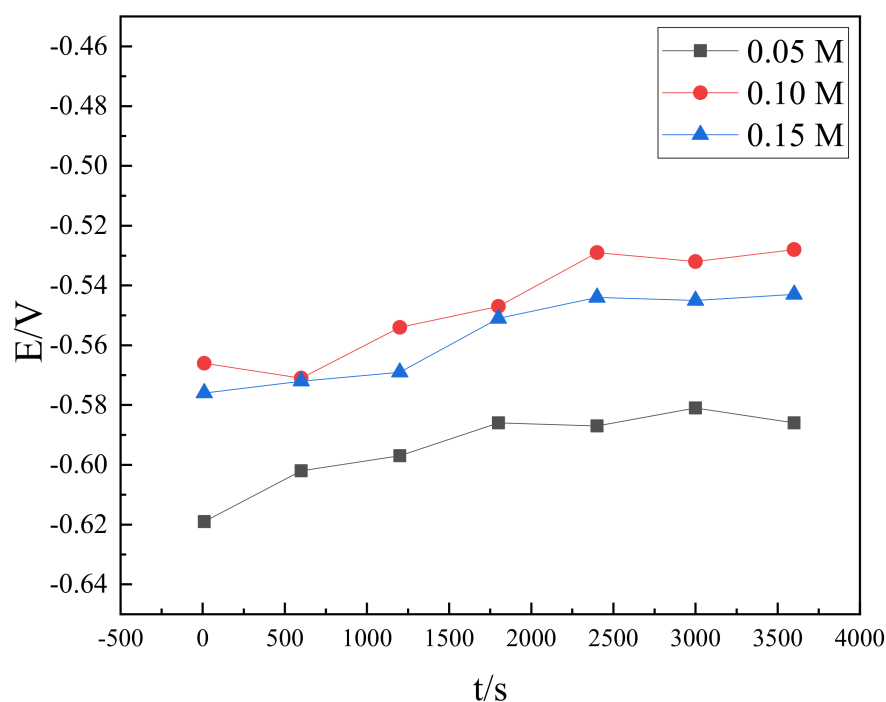


Figure 9. Open circuit potential of PANI/CeO₂ composite coatings prepared at different concentrations of ammonium acetate in 3.5 wt.% NaCl solution.

Figure 11 depicts the potentiodynamic polarization curves of PANI/CeO₂ composite coatings prepared at different concentrations of ammonium acetate in 3.5 wt.% NaCl solution. It is obvious that the corrosion potentials of the constructed PANI/CeO₂ coatings show a positive value compared to the pure mild steel substrate (approximately -0.923 V). The electrochemical parameters, as shown in Table 8, demonstrate that the I_{corr} value decreases from $34.62 \mu\text{A}\cdot\text{cm}^{-2}$ (blank sample) to 3.052, 0.199 and 1.608 for the prepared PANI/CeO₂ composite from 0.05 M, 0.10 M and 0.15 M ammonium acetate, respectively. The PANI/CeO₂ coating fabricated in the electrolyte containing 0.10 M ammonium acetate exhibits the highest inhibition efficiency of 99.4%.

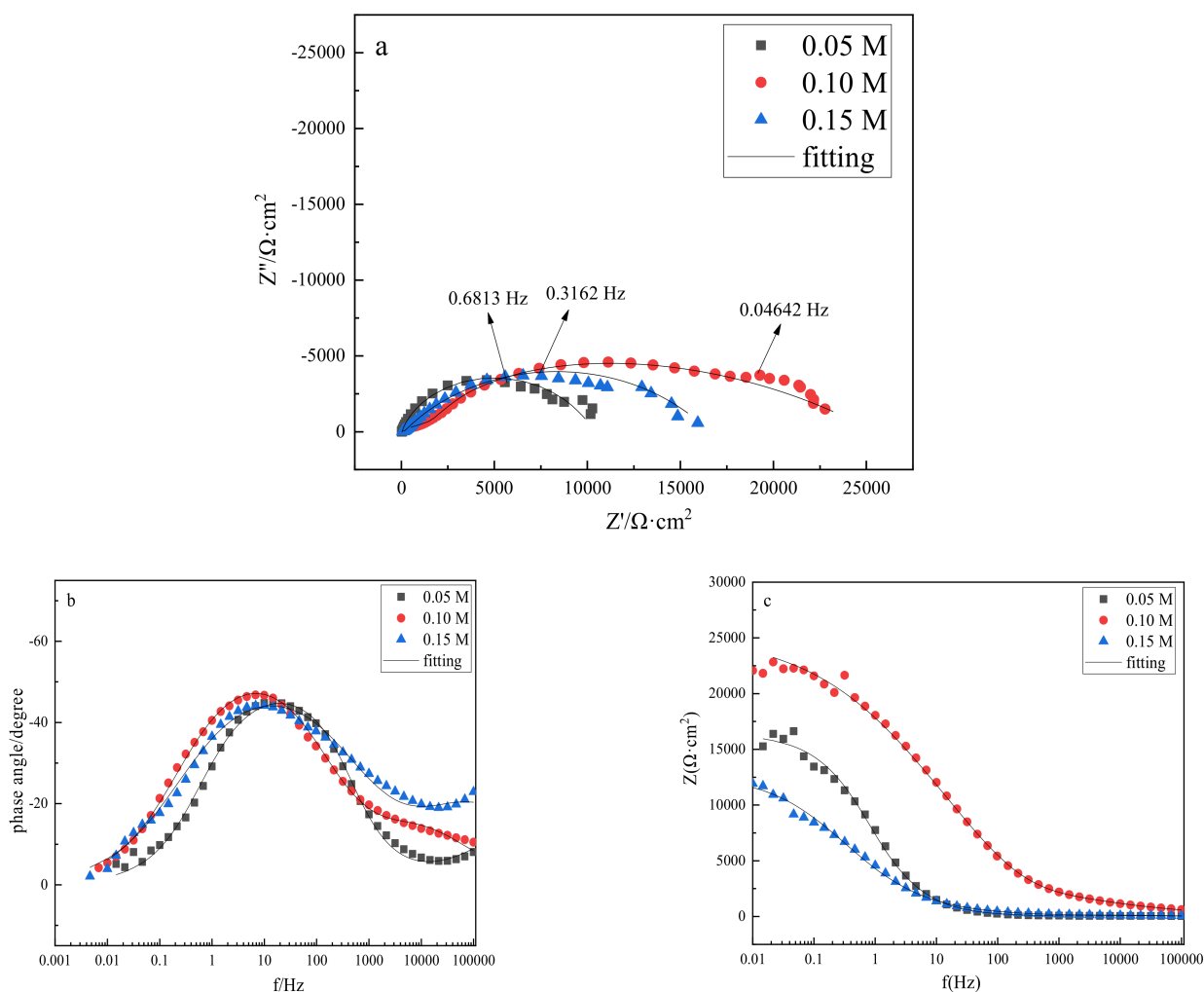


Figure 10. (a) Nyquist, (b,c) Bode plots of PANI/CeO₂ composite coatings prepared at different concentrations of ammonium acetate in 3.5 wt.% NaCl solution.

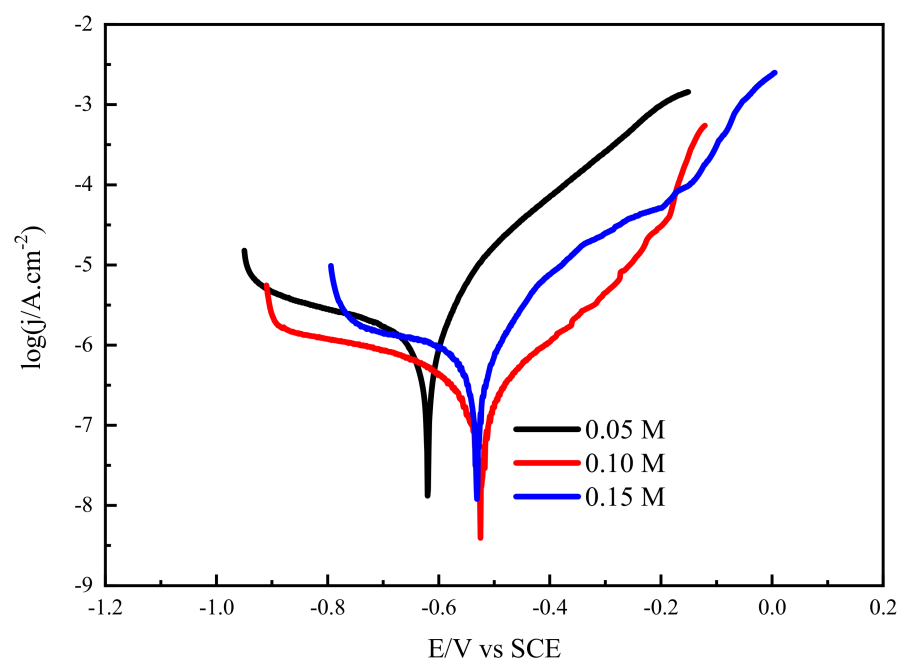


Figure 11. Potentiodynamic polarization curves of PANI/CeO₂ composite coatings prepared at different concentrations of ammonium acetate in 3.5 wt.% NaCl solution.

Table 7. EIS fitting results for PANI/CeO₂ composite coatings prepared at different concentrations of ammonium acetate in 3.5 wt.% NaCl solution.

Concentration (M)	R_{ct} $k\Omega \cdot cm^2$	CPE_{dl} $\Omega^{-1} \cdot cm^{-2} \cdot s^n$	n_c	R_c $\Omega \cdot cm^2$	CPE_c $\Omega^{-1} \cdot cm^{-2} \cdot s^n$	n_{dl}	χ^2 10^{-3}	R_p $k\Omega \cdot cm^2$	PE%
0.05	15.15	7.07×10^{-6}	0.832	673.4	5.15×10^{-6}	0.825	1.06	15.82	93.3
0.10	55.78	7.79×10^{-7}	0.899	4934	2.41×10^{-6}	0.842	1.25	60.71	98.3
0.15	22.73	3.28×10^{-6}	0.854	1101	4.08×10^{-6}	0.891	1.32	23.83	95.6

Table 8. Potentiodynamic polarization parameters of PANI/CeO₂ composite coatings prepared at different concentrations of ammonium acetate in 3.5 wt.% NaCl solution.

Concentration (M)	E_{corr} (V)	I_{corr} ($\mu A \cdot cm^{-2}$)	$-\beta_c$ ($mV \cdot dec^{-1}$)	β_a ($mV \cdot dec^{-1}$)	IE%
0.05	-0.615 ± 0.016	3.052 ± 0.06	315 ± 6.6	164 ± 4.5	91.2
0.10	-0.524 ± 0.013	0.199 ± 0.007	324 ± 7.2	173 ± 4.9	99.4
0.15	-0.528 ± 0.012	1.608 ± 0.05	309 ± 6.8	203 ± 5.5	95.4

3.2.3. pH

The electrolyte pH is a crucial factor that affects the adhesion of synthesized PANI/CeO₂ composite coating. The adhesion was measured to be grade 1, 0, and 3 for the electrolyte pH at 5.0, 5.5 and 6.0, respectively. The moderate electrolyte pH slows down the production of radical cations, allowing the polymer chains to align and grow more uniformly, leading to an improved adhesion to mild steel substrate. The open circuit potential of PANI/CeO₂ composite coatings prepared at different pH values in 3.5 wt.% NaCl solution is shown in Figure 12. It can be seen that the open circuit potential of the prepared hybrid PANI/CeO₂ coatings shifts slightly to the positive value during the soaking period. The finally reached stable E_{ocp} was much larger than the blank sample and pure PANI coating. The EIS plots of PANI/CeO₂ composite coatings prepared at different pH values in 3.5 wt.% NaCl solution are depicted in Figure 13. The electrolyte pH influences significantly the corrosion protection property of co-electrodeposited PANI/CeO₂ coatings. Typically, the PANI/CeO₂ coating electro-polymerized in the electrolyte with pH of 5.5 shows the largest diameter of the capacitive loops and exhibits the largest value of $Z_{0.01Hz}$, suggesting the best anti-corrosion capability. The fitted electrochemical parameters, as shown in Table 9, indicate that the R_p follows the order: pH = 5.5 ($60.71 k\Omega \cdot cm^2$) > pH = 5.0 ($22.03 k\Omega \cdot cm^2$) > pH = 6.0 ($11.68 k\Omega \cdot cm^2$).

Figure 14 displays the potentiodynamic polarization curves of PANI/CeO₂ composite coatings prepared under different pH conditions in 3.5 wt.% NaCl solution. Both the anodic and cathodic current density were reduced by the coated PANI/CeO₂ hybrid fabricated under different pH conditions. The calculated parameters are listed in Table 10. All these samples exhibit a positively shifted corrosion potential in comparison with the blank mild steel and pure PANI coating. On the other hand, the corrosion current density decreases approximately one order of magnitude for the deposited coating at pH of 5.0 and 6.0, and two orders of magnitude at pH value of 5.5, respectively. As a result, the fabricated PANI/CeO₂ composite coating at pH value of 5.5 possesses the highest IE of 99.4%. From the above analysis, the optimal co-electrodeposition condition was found to be: 0.3 mol/L aniline, 0.04 mol/L benzoic acid, 0.10 mol/L cerium nitrate, 0.10 mol/L ammonium acetate and pH of 5.5. The enhanced anti-corrosion property of PANI/CeO₂ composite coating may be ascribed to the synergistic effect of the PANI coating and the co-electrodeposited CeO₂ nanoparticles. Firstly, the bulk PANI coating protects the mild steel substrate from corrosion through the anodic passivation effect. On the other hand, the reduction of PANI coating from an emeraldine salt form to an undoped leuco form will release inhibitive

dopant ions, which then adsorbed onto the mild steel substrate surface to form a protective film. Then, the co-electrodeposited CeO_2 nanoparticles act as inorganic additives to fill the defects in the PANI coating, leading to a much denser and more compact structure. Moreover, when the corrosive electrolyte permeates the physical barrier and diffuses into the interface, the deposited CeO_2 nanoparticles can serve as corrosion inhibitors to form a stable cerium oxide layer and consequently restraint the propagation of corrosion.

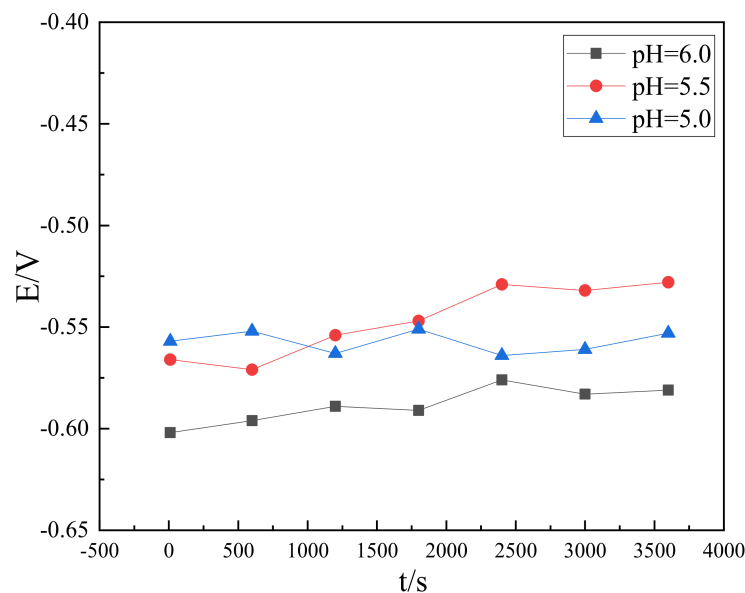


Figure 12. Open circuit potential of PANI/ CeO_2 composite coatings prepared at different pH values in 3.5 wt.% NaCl solution.

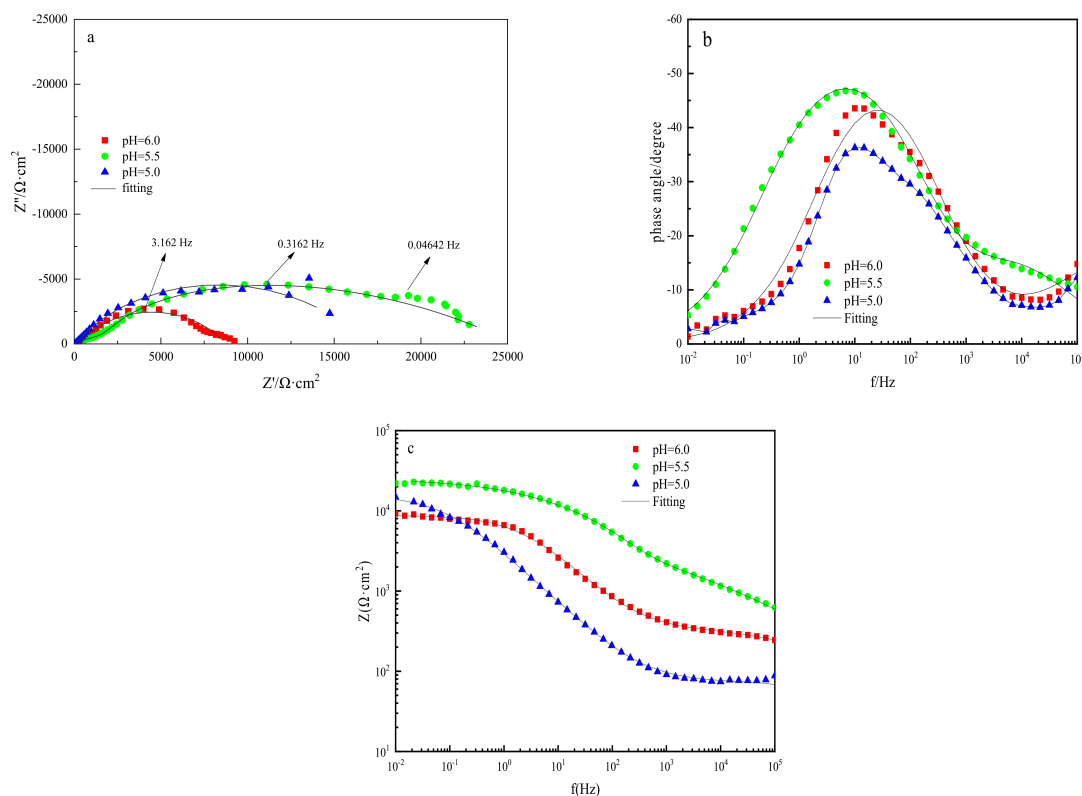
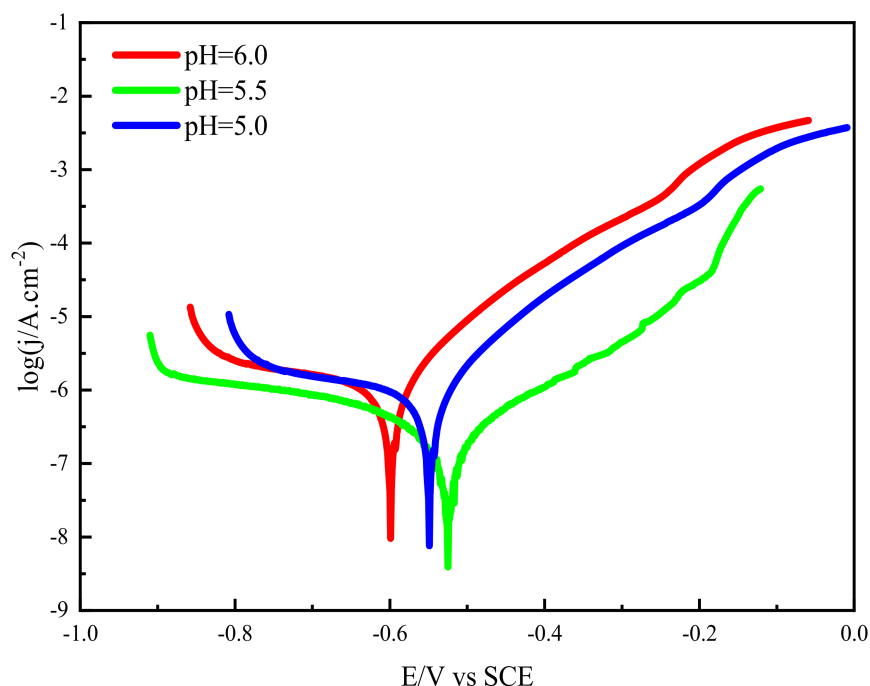


Figure 13. (a) Nyquist, (b,c) Bode plots of PANI/ CeO_2 composite coatings prepared at different pH values in 3.5 wt.% NaCl solution.

Table 9. EIS fitting results for PANI/CeO₂ composite coatings prepared under different pH conditions in 3.5 wt.% NaCl solution.

pH	R_{ct} $k\Omega \cdot cm^2$	CPE_{dl} $\Omega^{-1} \cdot cm^{-2} \cdot s^n$	n_c	R_c $\Omega \cdot cm^2$	CPE_c $\Omega^{-1} \cdot cm^{-2} \cdot s^n$	n_{dl}	χ^2 10^{-3}	R_p $k\Omega \cdot cm^2$	PE%
6.0	11.55	1.83×10^{-5}	0.803	131.9	7.49×10^{-6}	0.837	1.36	11.68	90.9
5.5	55.78	7.79×10^{-7}	0.899	4934	2.41×10^{-6}	0.842	1.25	60.71	98.3
5.0	21.12	2.95×10^{-5}	0.828	912.4	4.88×10^{-6}	0.824	1.77	22.03	95.2

**Figure 14.** Potentiodynamic polarization curves of PANI/CeO₂ coatings prepared under different pH conditions in 3.5 wt.% NaCl solution.**Table 10.** Potentiodynamic polarization parameters of PANI/CeO₂ composite coatings prepared under different pH conditions in 3.5 wt.% NaCl solution.

pH	E_{corr} (V)	I_{corr} ($\mu A \cdot cm^{-2}$)	$-\beta_c$ ($mV \cdot dec^{-1}$)	β_a ($mV \cdot dec^{-1}$)	IE%
6.0	-0.599 ± 0.011	3.080 ± 0.08	317 ± 6.8	166 ± 4.2	91.1
5.5	-0.524 ± 0.013	0.199 ± 0.007	324 ± 7.2	173 ± 4.9	99.4
5.0	-0.551 ± 0.013	1.419 ± 0.06	302 ± 6.9	147 ± 5.1	95.9

4. Conclusions

The electrolytic composition plays a crucial role in the structure and anti-corrosion performance of electro-polymerized coating. In this work, oxalic acid, hydrochloric acid, sulfuric acid, phosphoric acid and benzoic acid were utilized as electrodeposition electrolytes to prepare a PANI coating. The pitting occurred simultaneously when electro-polymerizing PANI coating using hydrochloric acid and sulfuric acid electrolyte, leading to a porous morphology. While depositing PANI coating in benzoic acid electrolyte, a compact and uniform structure with the adhesion grade of 0 was obtained. Electrochemical results indicated that the benzoic acid doped PANI coating possessed the smallest value of corrosion current density of $2.571 \mu A \cdot cm^{-2}$ and the largest inhibition efficiency of 92.6% among the investigated acidic electrolytes. Moreover, the impact of co-electrodeposition conditions, such as cerium nitrate concentration, ammonium acetate concentration and electrolyte pH

value, on the protective performance of co-electrodeposited PANI/CeO₂ composite coating was investigated and the optimal co-electrodeposition condition was found to be 0.3 mol/L aniline, 0.04 mol/L benzoic acid, 0.10 mol/L cerium nitrate, 0.10 mol/L ammonium acetate and pH of 5.5, under which condition the corrosion current density was decreased to 0.199 $\mu\text{A}\cdot\text{cm}^{-2}$ and the inhibition efficiency reached 99.4%. Future nanoscale investigations using techniques such as AFM, high-resolution electron microscopy or surface-sensitive spectroscopies could provide further insight into the distribution of cerium species, the morphology of the composite coating and the mechanisms responsible for the enhanced corrosion resistance, which significantly guide us to explore functional coatings with better protective properties.

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References

1. Htwe, Y.Z.N.; Pawlowska, S.; Jaafar, M. Emerging strategies for the fabrication of conductive hydrogels from conductive polymers and their composites for wearable sensors, energy storage, and biosensor applications: Methods, mechanisms, and future perspectives. *Adv. Mater. Technol.* **2026**, *11*, e01845.
2. Zhang, X.; Jiang, C.; Liang, J.; Wu, W. Electrode materials and device architecture strategies for flexible supercapacitors in wearable energy storage. *J. Mater. Chem. A* **2021**, *9*, 8099–8128.
3. Shahid, M.A.; Rahman, M.M.; Hossain, M.T.; Hossain, I.; Sheikh, M.S.; Rahman, M.S.; Uddin, N.; Donne, S.W.; Hoque, M.I.U. Advances in conductive polymer-based flexible electronics for multifunctional applications. *J. Compos. Sci.* **2025**, *9*, 42. [[CrossRef](#)]
4. Lu, Y.; Wang, Y.; Qi, X.; Lv, H.; Yin, A.; Liu, H.; Yu, S.; Zhao, W.; Wei, J. Aqueous conductive polymer composites with good printability and conductivity for flexible electronics. *J. Electron. Mater.* **2024**, *53*, 3143–3153. [[CrossRef](#)]
5. Jimoh, M.F.; Carson, G.S.; Anderson, M.B.; El-Kady, M.F.; Kaner, R.B. Direct fabrication of 3D electrodes based on graphene and conducting polymers for supercapacitor applications. *Adv. Funct. Mater.* **2025**, *35*, 2405569. [[CrossRef](#)]
6. Dubey, P.; Shrivastav, V.; Sundriyal, S.; Maheshwari, P.H. Sustainable nanoporous metal-organic framework/conducting polymer composites for supercapacitor applications. *ACS Appl. Nano Mater.* **2024**, *7*, 18554–18565. [[CrossRef](#)]
7. Pan, Y.; Zhang, J.; Guo, X.; Li, Y.; Li, L.; Pan, L. Recent advances in conductive polymers-based electrochemical sensors for biomedical and environmental applications. *Polymers* **2024**, *16*, 1597. [[CrossRef](#)] [[PubMed](#)]
8. García-Cabezón, C.; Godinho, V.; Pérez-González, C.; Torres, Y.; Martín-Pedrosa, F. Electropolymerized polypyrrole silver nanocomposite coatings on porous Ti substrates with enhanced corrosion and antibacterial behavior for biomedical applications. *Mater. Today Chem.* **2023**, *29*, 101433. [[CrossRef](#)]
9. Amegroud, H.; Boudalia, M.; Elhawary, M.; Garcia, A.J.; Bellaouchou, A.; Amin, H.M.A. Electropolymerized conducting polyaniline coating on nickel-aluminum bronze alloy for improved corrosion resistance in marine environment. *Colloids Surf. A Physicochem. Eng. Asp.* **2024**, *691*, 133909. [[CrossRef](#)]
10. Yin, Y.; Prabhakar, M.; Ebbinghaus, P.; da Silva, C.C.; Rohwerder, M. Neutral inhibitor molecules entrapped into polypyrrole network for corrosion protection. *Chem. Eng. J.* **2022**, *440*, 135739. [[CrossRef](#)]
11. Fang, J.; Xu, K.; Zhu, L.; Zhou, Z.; Tang, H. A study on mechanism of corrosion protection of polyaniline coating and its failure. *Corros. Sci.* **2007**, *49*, 4232–4242. [[CrossRef](#)]
12. Jeyaprabha, C.; Sathiyarayanan, S.; Venkatachari, G. Polyaniline as corrosion inhibitor for iron in acidic solutions. *J. Appl. Polym. Sci.* **2006**, *101*, 2144–2153. [[CrossRef](#)]

13. Lei, Y.; Qiu, Z.; Tan, N.; Du, H.; Li, D.; Liu, J.; Liu, T.; Zhang, W.; Chang, X. Polyaniline/CeO₂ nanocomposites as corrosion inhibitors for improving the corrosive performance of epoxy coating on carbon steel in 3.5% NaCl solution. *Prog. Org. Coat.* **2020**, *139*, 105430. [\[CrossRef\]](#)
14. Hu, C.; Li, T.; Yin, H.; Hu, L.; Tang, J.; Ren, K. Preparation and corrosion protection of three different acids doped polyaniline/epoxy resin composite coatings on carbon steel. *Colloids Surf. A Physicochem. Eng. Asp.* **2021**, *612*, 126069. [\[CrossRef\]](#)
15. Chen, H.; Fan, H.; Su, N.; Hong, R.; Lu, X. Highly hydrophobic polyaniline nanoparticles for anti-corrosion epoxy coatings. *Chem. Eng. J.* **2021**, *420*, 130540. [\[CrossRef\]](#)
16. Liu, T.; Wei, J.; Ma, L.; Liu, S.; Zhang, D.; Zhao, H. Effect of polyaniline-based plate on the anticorrosion performance of epoxy coating. *Prog. Org. Coat.* **2021**, *151*, 106109. [\[CrossRef\]](#)
17. Gao, M.; Wang, J.; Zhou, Y.; He, P.; Wang, Z.; Zhao, S. The performance of epoxy coatings containing polyaniline (PANI) nanowires in neutral salt, alkaline, and acidic aqueous media. *J. Appl. Polym. Sci.* **2020**, *137*, 49049. [\[CrossRef\]](#)
18. Wang, T.; Tan, Y.-J. Understanding electrodeposition of polyaniline coatings for corrosion prevention applications using the wire beam electrode method. *Corros. Sci.* **2006**, *48*, 2274–2290. [\[CrossRef\]](#)
19. Wei, Y.; Wang, J.; Jia, X.; Yeh, J.-M.; Spellane, P. Polyaniline as corrosion protection coatings on cold rolled steel. *Polymer* **1995**, *36*, 4535–4537. [\[CrossRef\]](#)
20. Li, P.; Tan, T.C.; Lee, Y.J. Corrosion protection of mild steel by electroactive polyaniline coatings. *Synth. Met.* **1997**, *88*, 237–242. [\[CrossRef\]](#)
21. Krajić, M.; Mandić, Z.; Duić, L. Inhibition of steel corrosion by polyaniline coatings. *Corros. Sci.* **2003**, *45*, 181–198. [\[CrossRef\]](#)
22. Moradi, M.; Marashi, P.; Rezaei, M. An experimental study and Monte Carlo simulation about the polyaniline coating dopants impact on long-time corrosion resistance of 304 SS. *J. Ind. Eng. Chem.* **2024**, *129*, 278–293. [\[CrossRef\]](#)
23. Calado, L.M.; Taryba, M.G.; Carmezim, M.J.; Montemor, M.F. Self-healing ceria-modified coating for corrosion protection of AZ31 magnesium alloy. *Corros. Sci.* **2018**, *142*, 12–21. [\[CrossRef\]](#)
24. Guergova, D.; Stoyanova, E.; Stoychev, D.; Avramova, I.; Stefanov, P. Self-healing effect of ceria electrodeposited thin films on stainless steel in aggressive 0.5 mol/L NaCl solution. *J. Rare Earths* **2015**, *33*, 1212–1227. [\[CrossRef\]](#)
25. Hernández-Montes, V.; Buitrago-Sierra, R.; Echeverry-Rendón, M.; Santa-Marín, J.F. Ceria-based coatings on magnesium alloys for biomedical applications: A literature review. *RSC Adv.* **2023**, *13*, 1422–1433. [\[CrossRef\]](#) [\[PubMed\]](#)
26. Han, X.; Guo, R.; Niu, B.; Yan, H. Enhanced corrosion resistance of epoxy resin coating via addition of CeO₂ and benzotriazole. *Chin. J. Chem. Eng.* **2024**, *67*, 89–96. [\[CrossRef\]](#)
27. Chen, C.; Dong, S.; Hou, R.; Hu, J.; Jiang, P.; Ye, C.; Du, R.; Lin, C. Insight into the anti-corrosion performance of electrodeposited silane/nano-CeO₂ film on carbon steel. *Surf. Coat. Technol.* **2017**, *326*, 183–191. [\[CrossRef\]](#)
28. Shetty, K.; Jayadev; Raj, K.; Mohan, N. Synthesis, characterization and corrosion studies of polyaniline(PANI)/cerium dioxide(CeO₂) nano composite. *Mater. Today Proc.* **2020**, *27*, 2158–2163. [\[CrossRef\]](#)
29. Sasikumar, Y.; Kumar, A.M.; Gasem, Z.M.; Ebenso, E.E. Hybrid nanocomposite from aniline and CeO₂ nanoparticles: Surface protective performance on mild steel in acidic environment. *Appl. Surf. Sci.* **2015**, *330*, 207–215. [\[CrossRef\]](#)
30. Alsaad, A.M.; Al-Hmoud, M.; Rababah, T.M.; Marashdeh, M.W.; Aljaafreh, M.J.; Alrub, S.A.; Binzowaimil, A.; Telfah, A. Synthesized PANI/CeO₂ nanocomposite films for enhanced anti-corrosion performance. *Nanomaterials* **2024**, *14*, 526. [\[CrossRef\]](#) [\[PubMed\]](#)
31. Zhou, H.; Du, X.; Yang, Z.; Chen, Y. One-step in situ electrochemical synthesis of polyaniline/CeO₂ composite coating for enhanced corrosion protection of mild steel. *Coatings* **2025**, *15*, 74. [\[CrossRef\]](#)
32. ISO 2409:2020(E); Paints and Varnishes-Cross-Cut Test. International Organization for Standardization: Geneva, Switzerland, 2020.
33. John, S.; Joseph, B.; Aravindakshan, K.K.; Joseph, A. Inhibition of mild steel corrosion in 1 M hydrochloric acid by 4-(N,N-dimethylaminobenzilidene)-3-mercapto-6-methyl-1,2,4-triazin (4H) -5-one (DAMMT). *Mater. Chem. Phys.* **2010**, *122*, 374–379.
34. Chen, Y.; Liu, Y.W.; Xie, Y.; Zhang, H.H.; Du, X.Q.; Zhang, Z. Preparation of hydrophobic silane/graphene oxide composite coating implanted with benzotriazole to improve the anti-corrosion performance of copper. *J. Alloys Compd.* **2021**, *893*, 162305. [\[CrossRef\]](#)
35. Ren, Y.J.; Zeng, C.L. Effect of conducting composite polypyrrole/polyaniline coatings on the corrosion resistance of type 304 stainless steel for bipolar plates of proton-exchange membrane fuel cells. *J. Power Sources* **2008**, *182*, 524–530. [\[CrossRef\]](#)
36. Santos, J.R.; Mattoso, L.H.; Motheo, A.J. Investigation of corrosion protection of steel by polyaniline films. *Electrochim. Acta* **1998**, *43*, 309–313. [\[CrossRef\]](#)
37. Nawaz, M.; Shakoor, R.A.; Kahraman, R.; Montemor, M.F. Cerium oxide loaded with Gum Arabic as environmentally friendly anti-corrosion additive for protection of coated steel. *Mater. Des.* **2021**, *198*, 109361. [\[CrossRef\]](#)
38. Qian, Y.; Zheng, W.; Chen, W.G.; Feng, T.; Liu, T.X.; Fu, Y.Q. Enhanced functional properties of CeO₂ modified graphene/epoxy nanocomposite coating through interface engineering. *Surf. Coat. Technol.* **2021**, *409*, 126819. [\[CrossRef\]](#)

39. Annibaldi, V.; Rooney, A.D.; Breslin, C.B. Corrosion protection of copper using polypyrrole electrosynthesised from a salicylate solution. *Corros. Sci.* **2012**, *59*, 179–185. [[CrossRef](#)]
40. Torresi, R.M.; de Souza, S.; da Silva, J.E.P.; de Torresia, S.I.C. Galvanic coupling between metal substrate and polyaniline acrylic blends: Corrosion protection mechanism. *Electrochim. Acta* **2025**, *50*, 2213–2218.
41. Spinks, G.M.; Dominis, A.J.; Wallace, G.G.; Tallman, D.E. Electroactive conducting polymers for corrosion control. *J. Solid State Electrochem.* **2002**, *6*, 85–100. [[CrossRef](#)]
42. Arunoday, M.; Premkumar, K.P.; Kumar, R.; Subasri, R. Multifunctional, environmental coatings on AA2024 by combining anodization with sol-gel process. *Ceram. Int.* **2022**, *48*, 10969–10978. [[CrossRef](#)]

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