Iraqi Journal of Physics, 2025 *Vol.23, No.1, PP. 85-93*
https://doi.org/10.30723/ijp.v23i1.1145 *P-ISSN: 2070-4003*
E-ISSN: 2664-5548

Evaluation of Corrosion Protection of Pipeline Steel by Blend Coatings

Mariam Zuhair[1a*] and Ahmed Qasim Abdullah[1b]
[1]*Department of Physics, College of Science, University of Baghdad, Baghdad, Iraq*
[a*]Corresponding author: maryumama@gmail.com

Abstract
This paper aimed to test the epoxy and polyester blends as an organic coating on mild steel against the harsh marine environment (NaCl 3.5 wt%) that causes corrosion. The electrochemical impedance spectroscopy (EIS) and fitting impedance data by ZsimpWin 3.22 software were used to estimate the barrier of the samples for different exposure times (30, 60, 90, and 120 min). One equivalent electrical circuit was used to fix the physical barrier to get an appropriate fitting. Epoxy and polyester blend coating showed excellent corrosion protection for steel. The blend coating showed better protection and stability against aggressive salt solutions over time. The connection between the coating film's dielectric properties (impedance spectrum) and how it acts as a physical barrier protection tells us about the electrochemical process's capacitive behavior. It lets us guess how it will be a barrier to protection in the real world. The observation is the radius of a semi-circle of a real part and the imaginary part of impedance (Z) in the Nyquist plot. The exponential power (n) of the constant phase element (CPE) is much less than one, indicating that CPE is far from a pure capacitor. All the phase angles for all and impedance with frequency in the Bode plot showed behavior similar to immersion times. Atomic force microscopy (AFM) appears as a thin peak topography with uniform disruption, which refers to a constant roughness for the specimen surface.

Article Info.

Keywords:
Corrosion, Coating, EIS, Nyquist Plot, Equivalent Circuit.

Article history:
Received: Jun.10, 2023
Revised: Aug.13, 2023
Accepted:Dec.09, 2023
Published:Mar.01,2025

1. Introduction
Due to their affordability, steel and iron are the most widely used metals [1]. Environmental conditions cause chemical reactions, known as corrosion, that deteriorate metals [2, 3]. Corrosion can be galvanic, stress, general, localised, intergranular, fretting, pitting, crevice, etc. [4, 5]. In a corrosion cell, an anode, cathode, and electrolyte solution come into contact with the metal. Anode ionic species dissolved in electrolyte. Electrons move from the anode to the cathode, creating a current that measures metal corrosion. Metal deposition, anodic, and cathodic reactions can occur on metal surfaces. Metal deposition neutralises metals [6, 7]. When a metal reacts with an electrolyte, it leaves its neutral state and releases ions that create a corrosion current. Finally, the cathode consumes ions released by the anodic process. Steel is mostly iron (Fe), which is reduced in a blast furnace with carbon from ores like hematite (Fe_2O_3) [8, 9]. Simple chemical terms describe the reduction:

$$2Fe_2O_3 + 3C \rightarrow 4Fe + 3CO_2 \quad (1)$$

Steelmaking requires high temperatures and energy. Moisture and oxygen cause steel to return to its original form: The chemical reaction is:

$$Fe + O_2 + H_2O \rightarrow Fe_2O_3.H_2O \quad (2)$$

The thermodynamics of corrosion, which deals with chemical equilibrium and energy shifts, explains metals and metal oxides' tendency to revert. Thermodynamics only offers information on a reaction tendency to occur [10]. Fig.1 shows that steel will rust if exposed to moisture and oxygen.

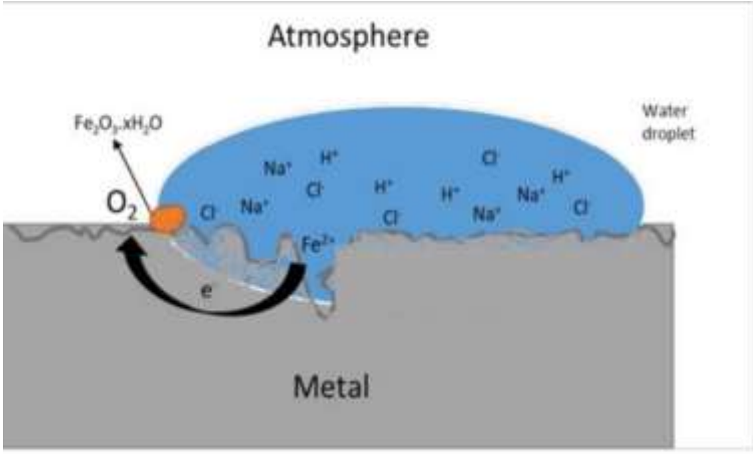

Figure 1: A depiction of the reaction between a coated steel substrate with a water droplet from the atmosphere [10].

Corrosion-related repairs, maintenance, and replacement cost 4% of South Africa's gross domestic product (GDP). GDP measures worldwide economic activity by tracking consumer spending on goods and services [11]. New technologies and science have intrigued researchers in material integration. Corrosion remains a big financial issue [19]. Corrosion's effects have been widely discussed in recent years. Corrosion causes material waste, pollution, and economic and environmental losses. These effects cause structures to break prematurely; compromising safety [12]. Organic coating is the most frequently used approach for metal corrosion protection. Most coating systems epoxies, acrylics, polyurethanes have environmental concerns. Precautionary measures fail. Reinforced polymers can withstand harsh situations. Organic coatings provide short-term protection, but they require periodic infrastructure replacement and surface repainting; thus, there is a need for long-term alternatives. Zinc galvanising, phosphating, inhibitors, CCCs, and Cp are the current approaches. Rain acidity affects zinc corrosion in outdoor metallic coatings [13, 14]. This work aims to protect pipelines from corrosion using the polymer coating method. This includes protection with metallic coating using the hot-dip method and polymer coating as an electrical insulator. The procedure is done by covering the outside of the pipeline with a protective film or coating to stop corrosion and other types of damage that can happen over time. The coating helps extend the life of the pipeline by protecting it from corrosion while reducing the risk of leakage or other forms of damage. Economically, it is important for the country as it saves millions of dollars.

2. Experimental Part

2. 1. Organic Coating Material

Organic coatings are protective coatings used to protect metal surfaces from corrosion, wear, and other types of damage. Various materials can be used for this purpose, including resins, solvents, and pigments, and they can be applied using multiple methods, such as spraying, brushing, or dip coating [15]. Here are some common materials used in organic coatings:

1. 2. 1. Epoxy

Epoxy is a class of thermosetting polymers commonly used as adhesives, coatings, and composite materials. Epoxy resins typically comprise two main components: a resin and a hardener. When these two components are mixed, a chemical reaction occurs, forming a solid, cross-linked material resistant to heat, chemicals, and mechanical stress [16].

Epoxy resins are known for their strong bonding properties, which make them useful in various applications, such as in the construction, automotive, and aerospace industries. They are also commonly used for repairing and restoring damaged materials, such as wood, metal, and concrete. In addition to their adhesive properties, epoxy resins are used as coatings to protect surfaces from corrosion, wear, and weathering. They are often applied to concrete floors, steel structures, and other surfaces that require a durable and protective coating. Epoxy composites are widely used in manufacturing high-performance materials, such as carbon fiber-reinforced composites, and in the aerospace and automotive industries to reduce weight and improve performance. Overall, epoxy resins and their derivatives have a broad range of applications and are valued for their strength, durability, and resistance to various types of damage [17].

1. 2. 2. Polyester

Polyester is a polymer category containing the ester functional group in their main chain. These polymers can be used in various applications, including textiles, packaging, and coatings. In particular, polyester resins are commonly used to produce composite materials, such as fiberglass-reinforced plastics, as in Table 1 [18]. When styrene and other unsaturated polyester polymers are mixed with a reactive diluent, they turn into thermosetting resins. By adding a catalyst and heat, the mixture can be hardened. This makes the polymer chains crosslink, forming a rigid, three-dimensional network [19].

Table1: Polyester Properties [18].

Property polyester	Physical state
Chemical formula	$(C_8H_8)n$
Viscosity	1000 pas
Gel conversion time	6 min
Specific weight	1.15
Bending resistance	164 & 176 N/mm^2
Bending factor	6.59 & 7.38 kN/mm^2
Tensile strength	88.3 & 91.5 N/mm^2
Tensile factor	7.71 & 9.30 kN/mm^2

Using a corroded pipeline
1. Cut the pipeline into circular pieces 1.5 cm radius and 3 mm thick.
2. Cut the tube into square pieces of dimensions (2.5×2.5 cm and 3 mm thick).
3. Coating the circular pieces with a metallic substance as well as a polymeric substance by the Hot-dip method after cleaning the pieces from corrosion.

2. 1. Hot-Dip Method

Hot-dip galvanizing (HDG) is a process of coating fabricated steel by immersing it in a bath of molten zinc at around 460 °C. When exposed to the atmosphere, the pure zinc (Zn) reacts with oxygen (O_2) to form zinc oxide (ZnO), which further reacts with carbon dioxide (CO_2) to form zinc carbonate ($ZnCO_3$), a fairly strong material that stops corrosion in many circumstances, thus protecting the steel. There are three fundamental steps in the hot-dip galvanizing process; surface preparation, galvanizing, and inspection [20], as shown in Fig. 2.

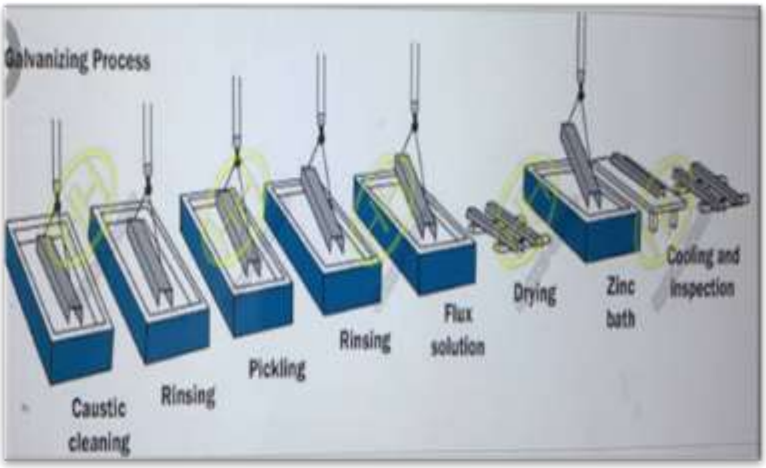

Figure 2: Hot- dip method [20].

3. Results and Discussion

3. 1. Electrochemical Impedance Spectroscopy (EIS)

The ZsimpWin 3.22 software [21] is used to fit the experimental impedance data to model equivalent circuits (Fig. 3). Next, we link the physicochemical processes occurring in the system to the circuit components and their configuration. The main objective of our study is to preserve pipelines from corrosion. A steel pipeline is coated with zinc as well as a polymeric material. Note that the capacitive effect depends on the immersion time since the imaginary part of the curves decrease with increasing immersion time. Also, resistance to charge transfer decreases over time. The reason is that aggressive species (like Cl-) penetrate the surface of the metal and cause corrosion. In order to perform the electrochemical impedance spectroscopy study, Nyquist diagrams and Bode diagrams were used as shown in Figs. 4, 5 and 6. The sample was immersed in NaCl solution for different periods (30, 60, 90, and 120 minutes), where it was noted. After 2 hours of exposure, the resistance of the solution increased. This increase can be explained by the fact that the solution has changed; for example, the solution may have become less conductive. Note that the solution obtained its resistance by crossing its semicircle with the real axis at high frequencies. In the first stage of immersion, a huge charge transfer resistance can be seen in the impedance plane, which explains the difficulty in seeing a complete semicircle [22]. After an hour and a half of immersion, the charge transfer resistance went down as the immersion time went up. This was because chloride ions were slowly penetrating the metal surface and interacting with the oxide layer. This caused the oxide layer to break down and the double-sided stainless steel to rust. Fig. 5 represents Bode plots, which represent the general behaviour of an equivalent circuit as a capacitor; they show the relationship between the frequency and phase angle. When the phase angle is close to 90°, the sample tends to be a pure or perfect capacitor, and that means excellent physical barrier properties, but if the phase angle is close to 0, the sample tends to be a resistor and far from a pure capacitor. As you can see in Fig. 6, Bode diagrams show how the equivalent general impedance of a circuit changes with frequency over two exposure times (30 and 60 minutes). The impedance of the circuit was higher at 60 min exposure time for all values of frequency [23]. Tables 2 and 3 show the stability of the electrical circuit at all times of immersion. We also note that all values of n_c are close to one. When the immersion time was 30 minutes, the n_c value was equal to the time the metal was uncoated, but when it was coated, the n_c value was equal to the same time as the immersion. In both cases, it was less than one, which indicates close proximity to the capacitive behaviour of the coating. At an immersion time of 60 min, the polymer-coated metal was the closest value to one [24, 25].

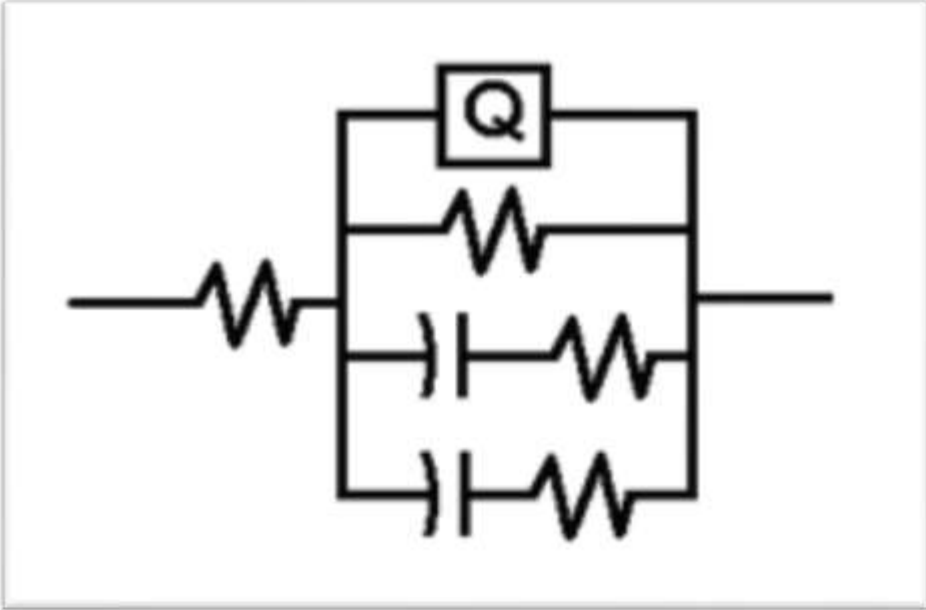

Figure 3: Equivalent circuit of EIS.

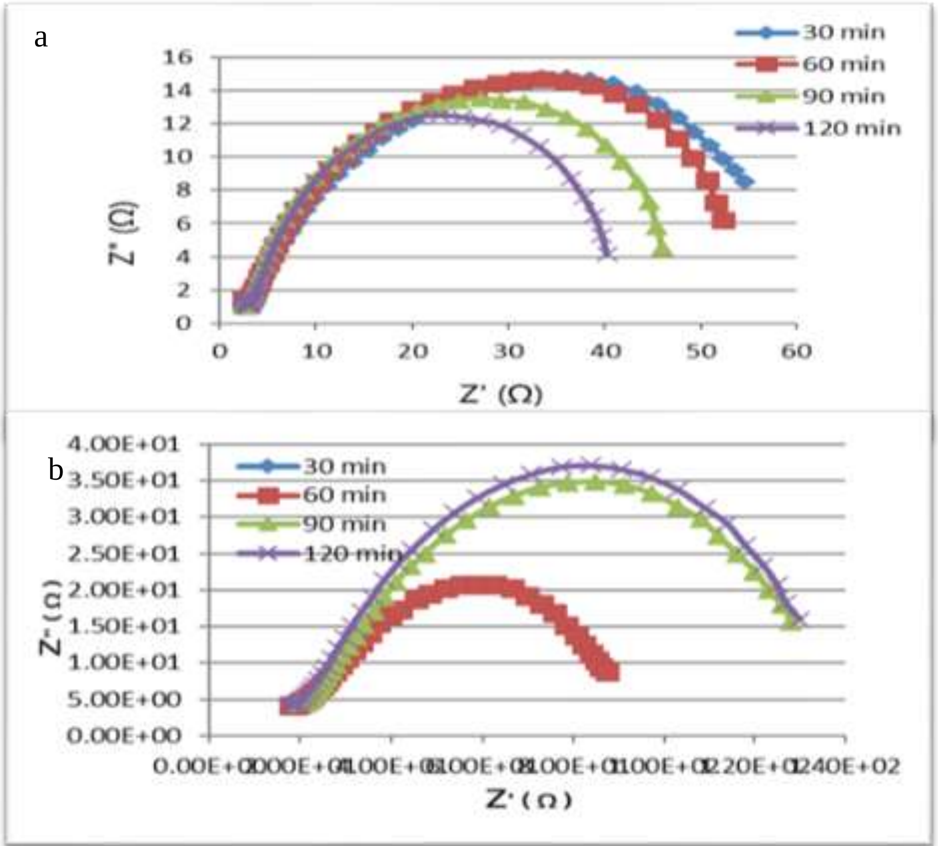

Figure 4: Nyquist impedance diagrams of (a) steel without coating, (b) steel with blend coating.

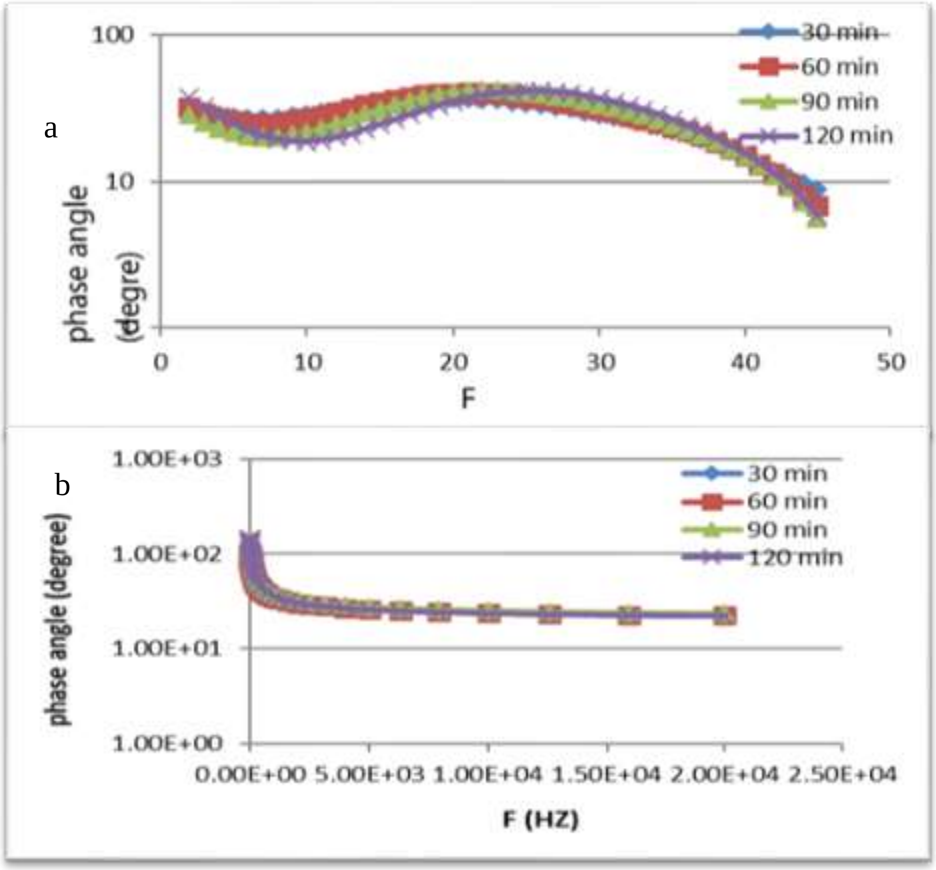

Figure 5: Bode plot of (a) steel without coating and (b) steel with blend coating.

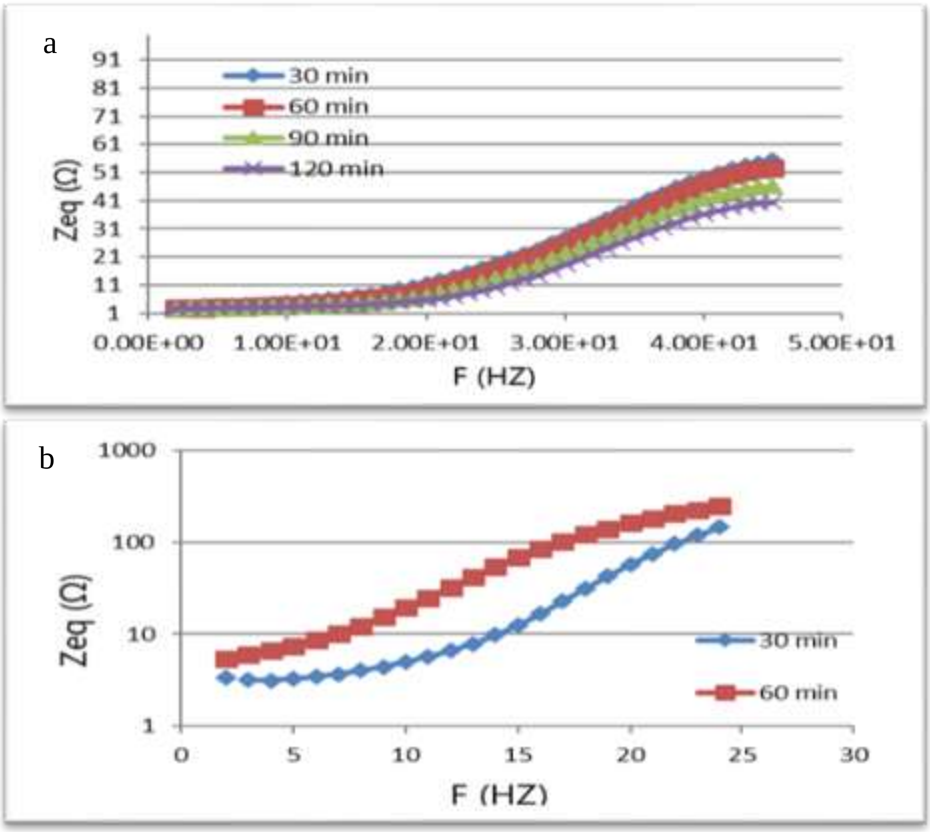

Figure 6: Bode plot of (a) steel without coating and (b) steel with blend coating.

Table 2: The Equivalent circuit configuration (R(QR)(CR)(CR)) and symbols (without coating).

Exposure Time (min)	R_u=R_s (Ω)	$Y_{coating}$ (S.sec)	n_c	R_{pore} (Ω)	C (F)	R(Ω)	C (F)	R_p(Ω)
30	9.7E-4	2.98E-5	0.3683	5.868 E4	7.637E5	6.883 E4	1.707E-7	1.311E4
60	1.708	5.577E-3	0.4289	29.47	1.178E-9	2.602 E-8	7.002E-6	33.12
90	4.915E-10	1.673E-3	0.4234	68.83	4.759E-5	7.712	9.871E-5	22.61
120	1.267	2.802E-3	0.4322	73	7.417E-5	14.02	3.736E-10	4.887

Table 3: The Equivalent circuit configuration (R(QR)(CR)(CR)) and symbols (Blend coating)

Exposure Time (min)	R_u=R_s (Ω)	$Y_{coating}$ (S.sec)	n_c	R_{pore} (Ω)	C (F)	R(Ω)	C (F)	R_p(Ω)
30	8.566E-6	2.217E-3	0.4113	72.43	2.046E-5	111.7	1.121E-5	15.84
60	0.7401	8.53E-6	0.9079	48.71	3.484E-5	4.237	1.389E-4	30
90	2.762	9.683E-6	0.6773	40.09	0.000149	18.43	6.164E-5	0.2329
120	1.431	2.156E-3	0.4627	46.18	9.072E-5	5.133	2.302E-6	0.02718

3. 2. Atomic Force Microscopy (AFM)

To better understand the sample surface properties, atomic force microscopy (AFM) was performed on the coatings. Fig. 7 from atomic force microscopy shows coatings that are all the same on zinc-coated steel and polyester-coated steel [26]. The coating method has particularly sharp peaks. The EIS result was confirmed by the AFM result, and it appears as a thin hump that seems to be uniformly distributed throughout the coating system [27, 28].

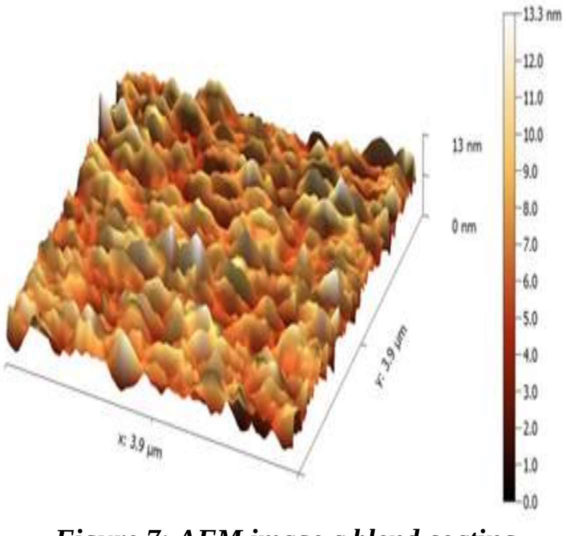

Figure 7: AFM image a blend coating.

4. Conclusions

The study looked at how well blend coating, which is often used to make pipelines, protects steel pipelines used in the oil industry from corrosion. The study's main goal was to find out how well it works. The study showed that EIS technology could analyses and evaluate the effectiveness of corrosion protection comprehensively and accurately. The study found that blend coating significantly improves corrosion protection efficiency, and the ideal thickness of blend coating should be in a certain range to achieve maximum protection. The study indicated that the quality of the coating should be regularly monitored and maintained to ensure proper protection.

Acknowledgements

The authors would like to thanks Physics Department, College of Science, University for their help and support.

Conflict of Interest

Authors declare that they have no conflict of interest.

References

1. Y. Yu, T. Wang, Y. Zhang, J. You, F. Hu, and H. Zhang, Chem. Recor. **23**, e202300109 (2023). DOI: 10.1002/tcr.202300109.
2. A. M. Abdel-Karim and A. M. El-Shamy, J. Bio. Tribo. Corros. **8**, 35 (2022). DOI: 10.1007/s40735-022-00636-6.
3. A. Rawat, S. R. Karade, and P. C. Thapliyal, Mat. Today Proce. **In Press**, Corrected Proof (2023). DOI: 10.1016/j.matpr.2023.06.210.
4. E. Mattsson, *Basic Corrosion Technology for Scientists and Engineers* (CRC Press, 2023).
5. D. Xu and S. Guo, *Corrosion Characteristics, Mechanisms and Control Methods of Candidate Alloys in Sub-and Supercritical Water* (China, Springer Nature, 2021).
6. J. Wang, M. Du, G. Li, and P. Shi, J. Clean. Product. **373**, 133658 (2022). DOI: 10.1016/j.jclepro.2022.133658.
7. Z. Wu, J. Zou, Y. Li, E. J. Hansen, D. Sun, H. Wang, L. Wang, and J. Liu, Small **19**, 2206634 (2023). DOI: 10.1002/smll.202206634.
8. M. K. Zadeh, M. Yeganeh, M. T. Shoushtari, and A. Esmaeilkhanian, Synth. Met. **274**, 116723 (2021). DOI: 10.1016/j.synthmet.2021.116723.
9. U. Brandner and M. Leuchtenmueller, Int. J. Hydro. Ener. **49**, 775 (2024). DOI: 10.1016/j.ijhydene.2023.07.189.
10. S. A. Al Kiey, M. S. Hasanin, and F. E.-T. Heakal, Sci. Rep. **12**, 13209 (2022). DOI: 10.1038/s41598-022-17386-7.
11. D. Northwood and N. Faldu, Proceedings of the Australasian Corrosion Association's Annual Conference: Corrosion and Prevention (Melbourne, Australia The Australasian Corrosion Association (ACA), 2019). p. 24.
12. J. Aslam, C. Verma , D. K. Verma, and R. Aslam, *Carbon Allotropes: Nanostructured Anti-Corrosive Materials* (Berlin, Boston, De Gruyter, 2022).
13. R. O. Medupin, K. O. Ukoba, K. O. Yoro, and T.-C. Jen, Mat. Today Sustain. **22**, 100373 (2023). DOI: 10.1016/j.mtsust.2023.100373.
14. S. O. Pehkonen and S. Yuan, *Interface Science and Technology* (London, UK, Elsevier, 2018).
15. F. Seidi, M. Jouyandeh, M. Taghizadeh, A. Taghizadeh, H. Vahabi, S. Habibzadeh, K. Formela, and M. R. Saeb, Materials **13**, 2881 (2020). DOI: 10.3390/ma13122881.
16. X. Zhao, Y. Long, S. Xu, X. Liu, L. Chen, and Y.-Z. Wang, Mat. Today **64**, 72 (2023). DOI: 10.1016/j.mattod.2022.12.005.
17. S. M. Gad, X. Zhou, S. B. Lyon, and S. Emad, Prog. Org. Coat. **174**, 107266 (2023). DOI: 10.1016/j.porgcoat.2022.107266.
18. M. Jaffe and J. D. Menczel, *Thermal Analysis of Textiles and Fibers* (Duxford, UK, Woodhead Publishing, 2020).
19. A. T. Shahid, M. Hofmann, M. Garrido, J. R. Correia, and I. C. Rosa, Materials **16**, 5411 (2023). DOI: 10.3390/ma16155411.
20. M. Y. Khalid, A. Kamal, A. Otabil, O. Mamoun, and K. Liao, Chem. Eng. J. Adv. **16**, 100537 (2023). DOI: 10.1016/j.ceja.2023.100537.
21. A. A. Yaqoob, M. N. Mohamad Ibrahim, K. Umar, S. A. Bhawani, A. Khan, A. M. Asiri, M. R. Khan, M. Azam, and A. M. Alammari, Polymers **13**, 135 (2021). DOI: 10.3390/polym13010135.
22. C. Ahner, P. Maaß, and P. Peißker, *Handbook of Dot-Dip Galvanization* (Germany, John Wiley & Sons, 2011).
23. H. Kania, Coatings **12**, 1207 (2022). DOI: 10.3390/coatings12081207.

24. A. Espinoza-Vázquez, L. J. Santiago Cárdenas, R. Galván-Martínez, A. Miralrio, M. Castro, A. Carmona Hernández, and R. Orozco-Cruz, J. Electroanalyt. Chem. **943**, 117599 (2023). DOI: 10.1016/j.jelechem.2023.117599.
25. L. A. Razzaq and A. Q. Abdullah, Iraqi J. Phys. **18**, 13 (2020). DOI: 10.30723/ijp.v18i46.544.
26. I. Milošev and G. S. Frankel, Journal of The Electrochemical Society **165**, C127 (2018). DOI: 10.1149/2.0371803jes.
27. A. Q. Abdullah, Iraqi J. Phys. **15**, 49 (2019). DOI: 10.30723/ijp.v15i33.139.
28. L. Xiaolu, H. Wang, Z. Guo, and Z. Peng, IEEE International Conference on Dielectrics (ICD) (Montpellier, France IEEE, 2016). p. 1081.

تقييم الحماية من التآكل لخطوط الأنابيب الفولاذية عن طريق الطلاء الممزوج

مريم زهير[1] واحمد قاسم عبدالله[1]

[1]قسم الفيزياء، كلية العلوم، جامعة بغداد، بغداد، العراق

الخلاصة

تركز الدراسة على تقييم الحماية من التآكل لخطوط الأنابيب الفولاذية عن طريق الطلاء الممزوج. المتغيرات البيئية تسبب تآكل المعادن، وقد فشلت الأساليب الوقائية. يشكل الانود والكاثود والإلكترو ليت خلية تآكل، والتي يمكن أن تسبب ترسبًا للمعادن وتفاعلات أنودية وكاثودية على الأسطح المعدنية. الصلب هو في الغالب الحديد، والذي يتم تقليله في فرن الصهر بالكربون. تم اختبار البوليمرات المركبة من الإيبوكسي والبوليستر لمعاوقة في الطلاءات العضوية. كانت تقنية EIS قادرة على تحليل وتقييم فعالية الحماية من التآكل بطريقة شاملة ودقيقة. تم تحليل البيانات باستخدام نموذج كهروكيميائية لتحديد معاملات الانتشار الكهربائي ومقاومة الانتقال الإلكتروني. وجدت الدراسة أن طلاء المزيج يحسن بشكل كبير من كفاءة الحماية من التآكل، ويجب أن تكون السماكة المثالية لطلاء المزيج في نطاق معين لتحقيق أقصى قدر من الحماية. أشارت الدراسة إلى أنه يجب مراقبة جودة الطلاء بانتظام وإجراء الصيانة الدورية لضمان استمرار الحماية المناسبة. بشكل عام، يمكن استنتاج أن تقنية EIS هي أداة قوية وفعالة لتقييم الحماية من التآكل لأنابيب الصلب المستخدمة في صناعة البترول. يمكن استخدام هذه التقنية لتحديد وتحسين فعالية أنظمة الحماية من التآكل الأخرى لزيادة عمر المنتج وتحسين جودة المنتج.

الكلمات المفتاحية: التأكل، الطلاء، مخطط نايكويست، EIS، الدائرة المكافئة.