Indonesian Physical Review
Volume 08 Issue 02, May 2025
P-ISSN: 2615-1278, E-ISSN: 2614-7904

Corrosion Resistance of PANI/Polymorphic-ZrO_2 Modified Epoxy Paint in High Salinity Environment

Munaji[1*], Rizki Dwi Ardika[1*], Nanang Suffiadi Akhmad[1], Albet Eka Pratama[1], Ahmad Rifai[1], Alfandy Kurnia Azam[1], Triwikantoro[2]

[1] *Department of Mechanical Engineering, Universitas Muhammadiyah Ponorogo, Indonesia*
[2] *Department of Physics, Faculty of Science and Data Analytics, Institut Teknologi Sepuluh Nopember, Surabaya Indonesia.*

Corresponding Authors E-mail: munaji@umpo.ac.id, rizkidwiardika@umpo.ac.id

Article Info

Article info:
Received: 12-12-2024
Revised: 07-04-2025
Accepted: 24-04-2025

Keywords:
Polymorphic; ZrO_2; PANI/ZrO_2; Corrosion

How To Cite:
Munaji, R. D. Ardika, N. S. Akhmad, A. E. Pratama, A. Rifai, A. K. Azam, Triwikantoro, "Corrosion resistance of PANI/POLYMORPHIC-ZrO_2 Modified Epoxy Paint in High Salinity Environment", Indonesian Physical Review, vol. 8, no. 2, p 417-428, 2025.

DOI:
https://doi.org/10.29303/ipr.v8i2.446.

Abstract

Corrosion in high-salinity environments remains a major concern in maintaining the durability and performance of metallic infrastructure. The use of conductive polymers and ceramic nanoparticles, such as polyaniline (PANI) and zirconia (ZrO_2), has emerged as a promising strategy to improve the corrosion resistance of protective coatings. This study aims to evaluate the effect of ZrO_2 polymorphic phases—tetragonal (t-ZrO_2), monoclinic (m-ZrO_2), and a mixture of tetragonal–monoclinic (tm-ZrO_2)—on the corrosion protection performance of PANI/ZrO_2-modified epoxy coatings applied on ST42 steel. The coatings were applied using spray coating. Compositions of ZrO_2 were varied at 2.5%, 5%, 7.5%, and 10% by weight. To simulate a marine environment, corrosion resistance was assessed using Tafel plot measurements in a 3.5% NaCl solution at room temperature. The results revealed that coatings containing t-ZrO_2 and tm-ZrO_2 phases exhibited significantly lower corrosion rates than those with m-ZrO_2. At 7.5% composition, the addition of ZrO_2 reduced the corrosion rate from 0.6710 mpy (without PANI/ZrO_2) to 0.3988 mpy (with PANI/m-ZrO_2), 0.0364 mpy (with PANI/t-ZrO_2) and 0.0212 mpy (with PANI/tm-ZrO_2). These findings highlight the critical role of ZrO_2 phase composition in improving coating performance. Incorporating t-ZrO_2 and tm-ZrO_2 into epoxy coatings presents a promising pathway to enhance corrosion resistance, offering valuable potential for applications in aggressive saline environments.

Introduction

Construction materials applied in high-salinity environments are susceptible to corrosion [1] [2] [3]. Corrosion can cause damage to ship structures, reducing the strength and toughness of the structure and causing economic losses [4]. To address this problem, ship structures are often manufactured using medium carbon steel AISI 1042 or ST42. The advantages of ST 42 steel are its high tensile strength and excellent welding, making it suitable for building ship hulls, decks, and other structural components [5]. Although this steel has fairly good corrosion resistance, it also requires additional protection with paint to extend its service life and maintain its structural integrity.

The use of paint as an anti-corrosion coating has long been carried out [6]. Although the industry has provided many choices of anti-corrosion coating paints, current anti-corrosion coating paints still have several weaknesses, including not being resistant to high temperatures, being less resistant to humid areas, and being less effective in the long term [7]. Therefore, research on increasing corrosion resistance continues to be carried out. These efforts include adding additives from plant extracts [8] [9] natural fibers [10], metal oxide ceramic materials [11] [12] [13] And polymer/oxide-based materials. Polymers/metal oxides that have been used for anti-corrosion materials include PANI/SiO_2 [14], PANI/Fe_2O_3 [15], and PANI/ZrO_2 [12] [16] [17].

Polyaniline/ZrO_2 (PANI/ZrO_2) composite is a widely studied polymer/metal oxide composite material due to its unique properties and vast application potential. Compared to other polymer/metal oxide composites, PANI/ZrO_2 has superior corrosion resistance due to its enhanced adhesion and high thermal stability. This material combines the properties of polyaniline with ZrO_2. The reported research starts with synthesis, characterization, and application. PANI/ZrO_2 composite is generally synthesized using the in-situ polymerization method. Exploration of PANI/ZrO_2 composite properties includes characterization of thermal properties, electrical properties, and electrochemical properties. PANI/ZrO_2 composite is more thermally stable than pure PANI. This composite thermal stability increase is considered to originate from the interaction between PANI and nano-ZrO_2 [18] [19]. Other research results show that based on TGA data analysis, the thermal stability of PANI/ZrO_2 is higher than PANI. The conductivity of PANI/ZrO_2 composite is around 11.27 S/cm, which is typical of semiconductors [20].

The corrosion resistance test shows that PANI/ZrO_2 shows better corrosion inhibition efficiency [16]. The application of a steel coating coated with PANI/ZrO_2 composite has a corrosion rate value in between, which is lower than paint-coated steel but higher than ZrO_2-coated steel [21] [22]. In this study, the utilization of PANI/ZrO_2 composite material as an additive for anti-corrosion coating paint will be developed.

As is known, ZrO_2 from previous studies has different phases, namely amorphous (a), tetragonal (t), monoclinic (m), and a mixture of tetragonal-monoclinic (tm). Then, the electrical properties of PANI/a-ZrO_2, PANI/m-ZrO_2, PANI/t-ZrO_2, and PANI/tm-ZrO_2 composites have also been studied [16]. While previous studies have focused on the electrical properties of PANI/ZrO_2 composites, this study specifically aims to determine the effect of ZrO_2 phase variations (tetragonal, monoclinic, and tetragonal-monoclinic) on the corrosion inhibition performance of PANI/ZrO_2 composites when used as anticorrosive coating additives. Previous studies that discuss the effect of various ZrO_2 phases on the corrosion inhibition efficiency of PANI/ZrO_2 when applied as paint additives are still very limited. Therefore, this study needs to be conducted.

Experimental Method

PANI/ZrO_2 composites were prepared using the in-situ polymerization method, where the polymerization of aniline monomers occurs together with the presence of ZrO_2. The ZrO_2 used includes three phases, namely tetragonal (t), monoclinic (m), and tetragonal-monoclinic (tm). The detailed synthesis and characterization of PANI/polymorphic-ZrO_2 has been reported in previous research [23]. This PANI/ZrO_2 composite is in the form of dry sediment, then made into powder and sieved using a 400 mesh sieve.
Furthermore, the substrate specimen made of ST42 steel was formed into a cylinder with a diameter of 20 mm and a thickness of 5 mm as seen in Figure 1. The surface of the steel to be painted was then smoothed with sandpaper with grades 300, 600, and 1000. While the other side was connected with a cable using solder, this was intended as a connection to the corrosion test tool. Furthermore, all sides other than the surface coated with paint were wrapped with resin.

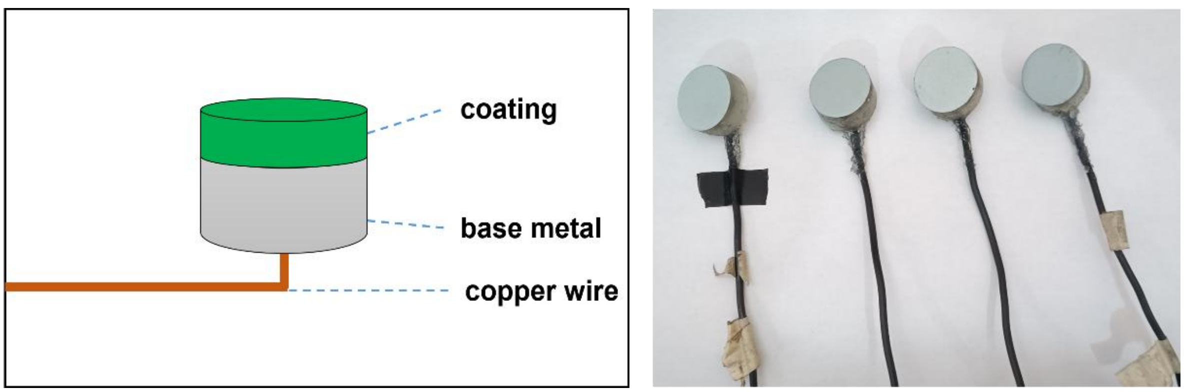

Figure 1. Test specimen

The next step is mixing the base coat (epoxy) with PANI/m-ZrO_2, PANI/t-ZrO_2, and PANI/tm-ZrO_2 materials with a specific ratio. Painting is done using the spray coating method. Painting is done in an optimal environment with a room temperature of 30°C, relative humidity of 40%, and good air circulation. The paint drying time is 24 hours. The sample list is shown in Table 1. After the paint is dry, the sample is tested for corrosion in a 3.5% NaCl solution according to ASTM G 44. Testing is carried out on days 1, 7, 14, and 21 of immersion. This corrosion test uses a three-electrode cell connected to a potentiostat/Galvanostat brand Gamry Reference 600 and a set of computers as data processors, as shown in Figure 2. The data obtained are then analyzed using Gamry Echem Analyst software, a Tafel plot.

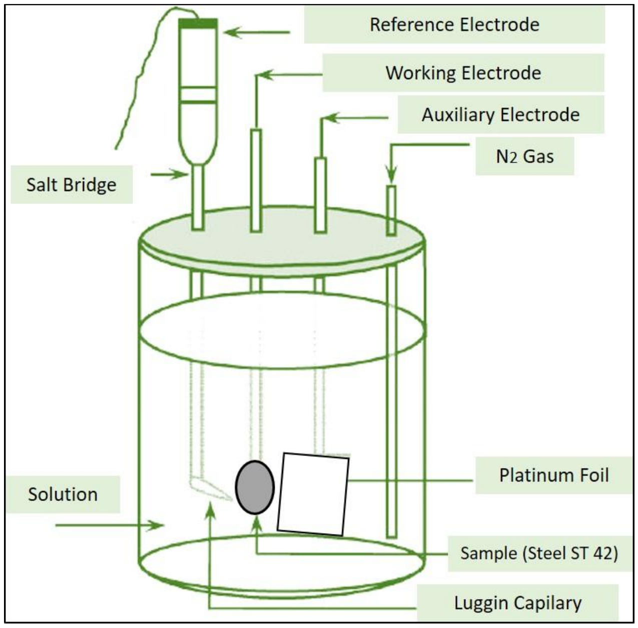

Figure 2. Test instrument for three-electrode potential cell polarization

Table 1. Coating composition on the sample

No.	Sample code	Annotation
1.	ST0	ST 42 without paint
2.	STC	ST 42 + paint
3.	STCM2	ST 42 + paint + PANI/2,5%m-ZrO_2
4.	STCM5	ST 42 + paint + PANI/5%m-ZrO_2
5.	STCM7	ST 42 + paint + PANI/7,5%m-ZrO_2
6.	STCM10	ST 42 + paint + PANI/10%m-ZrO_2
7.	STCT2	ST 42 + paint + PANI/2,5%t-ZrO_2
8.	STCT5	ST 42 + paint + PANI/5%t-ZrO_2
9.	STCT7	ST 42 + paint + PANI/7,5%t-ZrO_2
10.	STCT10	ST 42 + paint + PANI/10%t-ZrO_2
11.	STCTM2	ST 42 + paint + PANI/2,5%tm-ZrO_2
12.	STCTM5	ST 42 + paint + PANI/5%tm-ZrO_2
13.	STCTM7	ST 42 + paint + PANI/7,5%tm-ZrO_2
14.	STCTM10	ST 42 + paint + PANI/10%tm-ZrO_2

Result and Discussion

Corrosion resistance of paint coating-PANI/m-ZrO_2

The first additive used in metal primers is PANI/m-ZrO_2, a composite material with PANI matrix and monoclinic ZrO_2 filler. The mixture of paint-PANI/m-ZrO_2 shows varying corrosion resistance depending on the composition of m-ZrO_2, as shown in Figure 3.

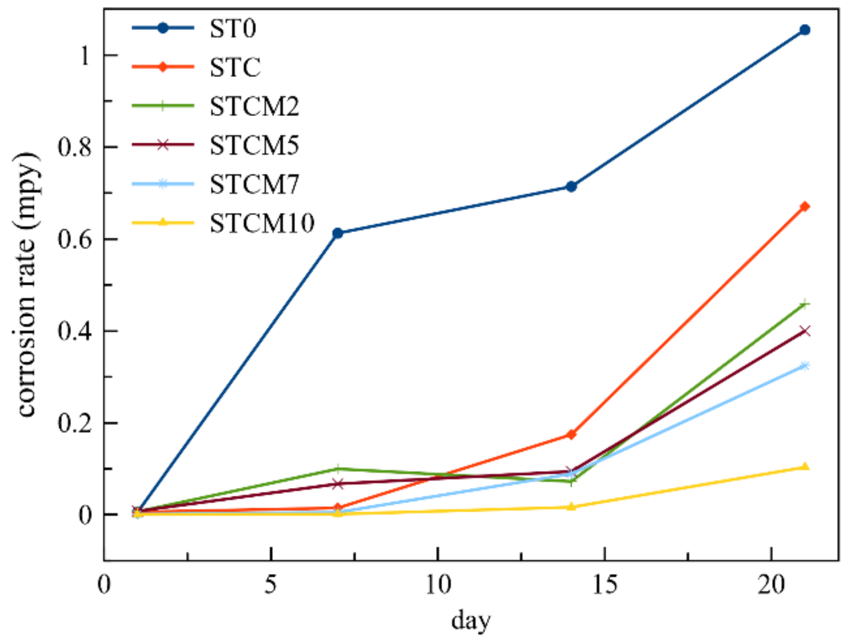

Figure 3. Corrosion rate of PANI/m-ZrO_2 paint coating

Based on Figure 3, it can be seen that the corrosion rate values in all samples increased, but the increase values varied. A high increase occurred in the ST0 sample, a metal substrate without anti-corrosion coating protection. The STC sample experienced a high increase in corrosion rate on days 14 to 21, caused by damage to the paint layer exposed to NaCl liquid, so the paint layer was not able to withstand the corrosion reaction that occurred. The STCM2 sample had the highest corrosion rate among the STCM5, STCM7, and STCM10 samples. This indicates that the percentage of m-ZrO_2 composition in the paint-PANI/m-ZrO_2 composite affects corrosion resistance. The higher the percentage of m-ZrO_2 composition, the better it inhibits the corrosion rate. However, further observations are still needed for m-ZrO_2 compositions above 10%.

The corrosion resistance of paint coating-PANI/t-ZrO_2

The next additive is PANI/t-ZrO_2, a composite material with PANI matrix and tetragonal ZrO_2 filler. The corrosion resistance of the PANI/t-ZrO_2 paint layer with various t-ZrO_2 compositions is shown in Figure 4. From the figure, it can be seen that there is a trend of increasing corrosion rate every day for each sample tested. Samples with the addition of PANI/t-ZrO_2 have a lower corrosion rate value than uncoated steel (STO) and coated with paint only (STC); this shows that the addition of PANI/t-ZrO_2 can increase the corrosion resistance of the paint layer.

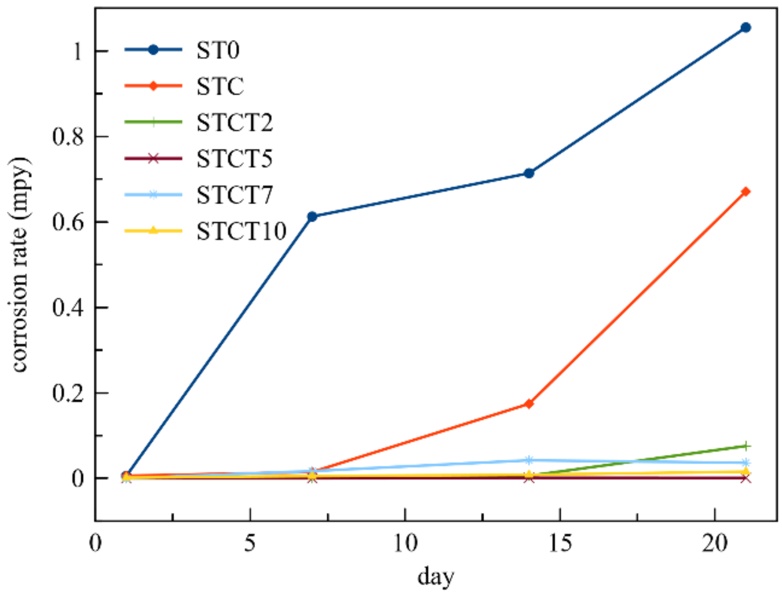

Figure 4. Corrosion rate of the PANI-ZrO_2 paint coating

The effect of composition variation also affects the effectiveness of corrosion protection provided by PANI/t-ZrO_2. STCT5 shows the best performance in protecting metals from corrosion. The relatively low corrosion rate indicates this compared to other compositions. STCT5 has an optimal balance between the protective effect of PANI and the barrier properties of ZrO_2, which provides effective protection against corrosive ion attacks. This composition can stabilize the passive layer and reduce the penetration rate of corrosive ions such as Cl^-, which is the main cause of corrosion in NaCl environments. On the other hand, the results for the compositions of PANI/t-ZrO_2 7% and 10% show higher corrosion rates, which are caused by the instability of the paint layer or the decrease in the effectiveness of the interaction of PANI and t-ZrO_2 at higher concentrations. With the addition of PANI/t-ZrO_2 7% and 10%. At these concentrations, although the corrosion protection increases compared to the paint sample without any addition, the effectiveness is not as high as at the concentration of STCT 5. This is likely due to the more significant agglomeration of ZrO_2 at high concentrations, thereby reducing the effectiveness of protection. At higher concentrations (7.5% and 10%), PANI/t-ZrO_2 particles are likely to tend to agglomerate [24], which reduces the effective surface area of the particles interacting with the polymer matrix and creates a preferential pathway for penetration of corrosive ions [25]. As a result, the protection provided is reduced when compared to the 5% composition.

Corrosion resistance of paint coating-PANI/tm-ZrO_2

Another additive used as a paint mixer is PANI/tm-ZrO_2, a composite material with a PANI matrix and ZrO_2 filler with a tetragonal-monoclinic mixed phase. The results of the corrosion resistance test of the PANI/tm-ZrO_2 paint coating are shown in Figure 5. The STCTM2 sample has the highest corrosion rate among the STCTM5, STCTM7, and STCTM10 samples. However, the corrosion rate of the PANI/tm-ZrO_2 coating remains lower than that of the paint coating alone.

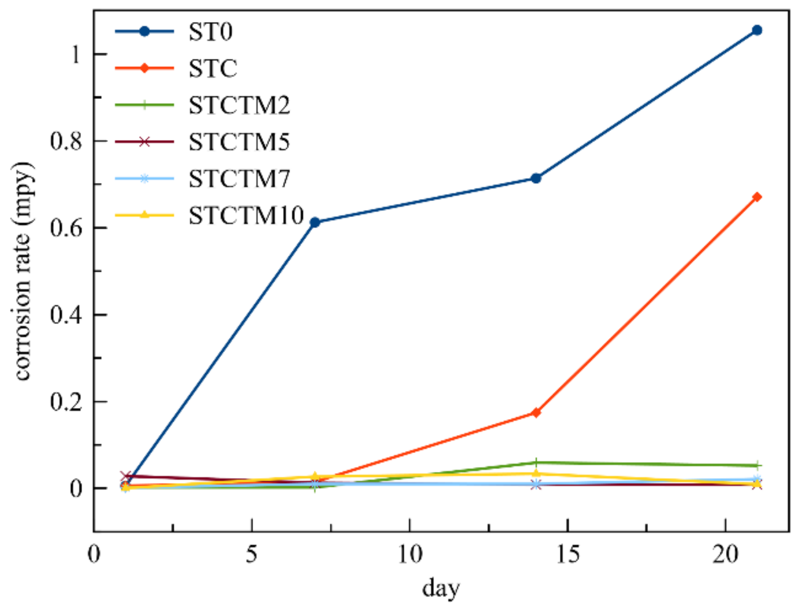

Figure 5. Corrosion rate of the PANI/tm-ZrO_2 paint coating

In contrast to the trend of corrosion rate on the PANI/m-ZrO_2 paint layer, where the higher the composition percentage, the better the ability to inhibit corrosion rate [26], the PANI/tm-ZrO_2 paint layer does not show a regular pattern. Samples STCTM5 and STCTM7 showed stable corrosion resistance, indicated by a relatively small increase in corrosion rate.

Effect of ZrO_2 polymorphism on corrosion resistance

The effect of ZrO_2 polymorphism on the corrosion resistance of the PANI/ZrO_2 paint layer can be seen from the comparison of the corrosion rate of the layer over a certain period, as shown in Figure 6. Based on the figure, it can be seen that the PANI/ZrO_2 paint layer with the monoclinic ZrO_2 phase tends to experience a faster increase in corrosion rate than other phases. The layer containing 5% and 7.5% t-ZrO_2 and tm-ZrO_2 has a relatively stable corrosion rate. The corrosion rate of PANI/ZrO_2 modified paint coating at 7.5% ZrO_2 is shown in Table 2. Overall, the layer containing tm-ZrO_2 has good corrosion resistance (low corrosion rate). This shows that ZrO_2 polymorphism affects corrosion resistance. Monoclinic crystals tend to have a cube shape with the same length and sides [25] [27]. This shape causes the tendency of PANI/m-ZrO_2 particles to be round. Tetragonal crystals tend to have a block shape with one side longer [17] [28]. This shape causes the tendency of PANI/t-ZrO_2 particles to be slightly oval [2]. This plays an important role in inhibiting the corrosion rate. An illustration of the role of ZrO_2 in inhibiting the corrosion rate is shown in Figure 7.

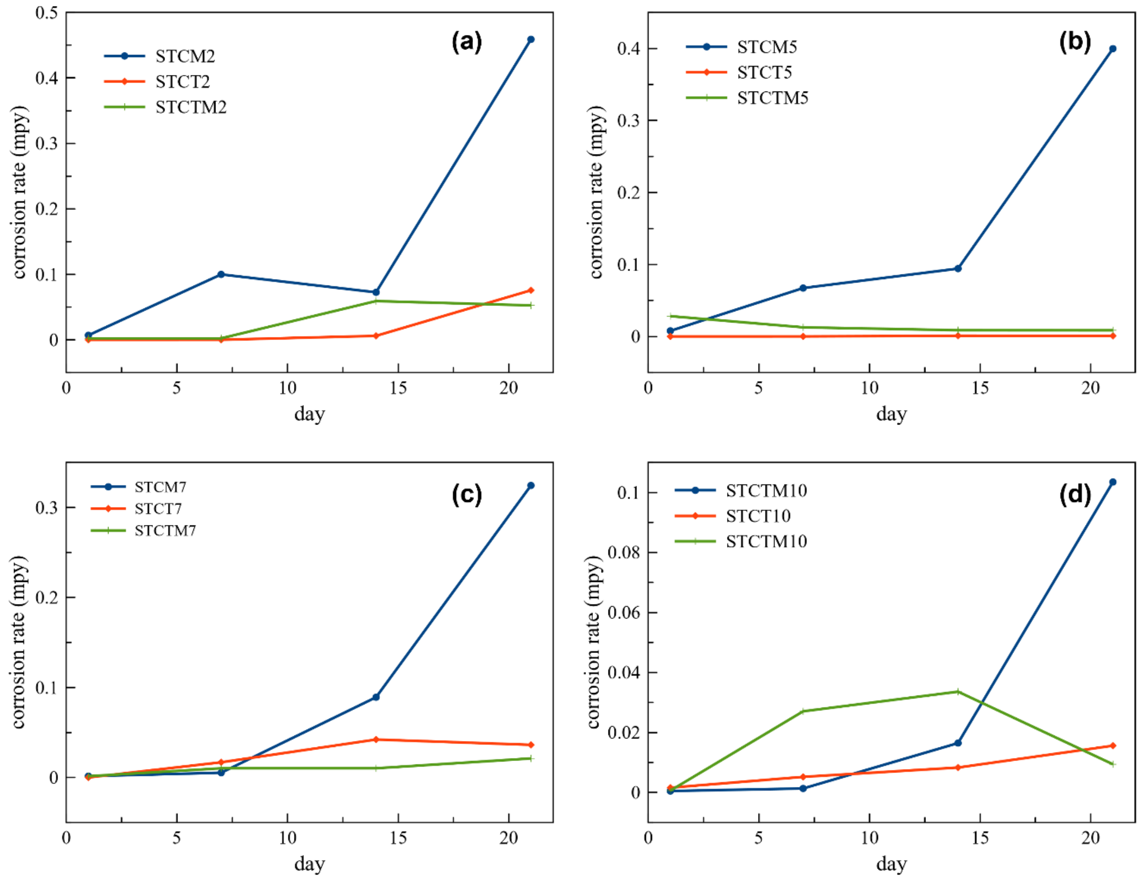

Figure 6. The corrosion rate of the PANI/ZrO_2 paint coating with ZrO_2 content: (a) 2.5%, (b) 5%, (c) 7.5%, and (d) 10%

Table 2. Corrosion Rate of PANI/ZrO_2 Coating (with 7.5% ZrO_2)

Day	Corrosion rate (mpy)			
	STC	STCM	STCT	STCTM
7	0.0148	0.0053	0.0169	0.0102
14	0.1744	0.0892	0.0422	0.0102
21	0.6710	0.3988	0.0364	0.0212

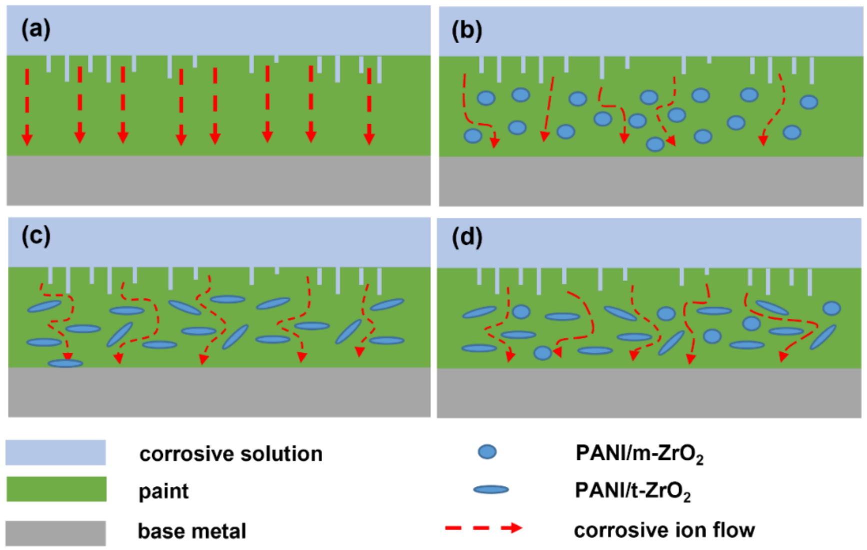

Figure 7. The corrosion protection mechanism of coatings: (a) pure paint, (b) paint-PANI/m-ZrO_2, (c) paint-PANI/t-ZrO_2, and (d) paint-PANI/tm-ZrO_2

Figure 7 (a) shows the relatively easier path of corrosive ions penetrating the paint layer. This is because no barrier particles are mixed with the paint, so the corrosive ion liquid penetrates straight through the paint layer. Figure 7 (b) explains the mechanism of corrosive ions penetrating the paint layer-PANI/m-ZrO_2. It appears that PANI/m-ZrO_2 functions as an inhibitor of the movement of corrosive ions penetrating the layer. Because PANI/m-ZrO_2 is spread across the layer, the path of the corrosive ion liquid has a winding path. Figure 7 (c) explains the mechanism of corrosive ions penetrating the paint layer with the addition of PANI/t-ZrO_2. It can be seen that PANI/t-ZrO_2 forms an inhibitor of the movement of corrosive ions penetrating the paint layer by forming a longer path than PANI/m-ZrO_2. Because there is PANI/t-ZrO_2 spread across the paint layer creates a winding and narrow path for corrosive ions to pass through, making the path of the corrosive ion liquid more difficult and hampered in penetrating the paint layer. Figure 7 (d) shows how corrosive ions penetrate the PANI/tm-ZrO_2 layer. This layer's tetragonal and monoclinic crystal structures create a more difficult path for corrosive ions to pass through. This mixed crystal form results in very few gaps, thus slowing the passage of corrosive ions to the metal surface. This mechanism illustrates how the PANI/tm-ZrO_2 layer effectively reduces the corrosion rate by blocking the penetration of ions that can cause damage to ST42 metal.

Conclusion

Adding PANI/polymorphic-ZrO_2 additives has been proven to increase the corrosion resistance of paint layers. The corrosion rate of the PANI/polymorphic-ZrO_2 paint layer is smaller than that of the pure paint layer. In sequence, corrosion resistance increases in paint layers that are given additional PANI/m-ZrO_2, PANI/t-ZrO_2, and PANI/tm-ZrO_2. The composition of polymorphic ZrO_2 affects corrosion resistance, where the compositions of 5% and 7.5% show relatively more stable performance. The mechanism of increasing corrosion resistance by PANI/polymorphic-ZrO_2 is related to its morphology, namely, by the formation of an inhibition of corrosive ion movement in the paint layer.

Acknowledgment

The Muhammadiyah University of Ponorogo funded this research through the Fundamental Research Scheme with contract number 44.17/V1.4/PN/2024.

References

[1] J. Zhou, S. Yin, Q. Fu, Q. Wang, Q. Huang, and J. Wang, "Microbial-induced concrete corrosion under high-salt conditions: Microbial community composition and environmental multivariate association analysis," *Int. Biodeterior. Biodegradation*, vol. 164, p. 105287, 2021.

[2] S. Zhao, Y. Xu, X. Xian, N. Liu, and W. Li, "Fabrication of porous Si@ C composites with core-shell structure and their electrochemical performance for Li-ion batteries," *Batteries*, vol. 5, no. 1, p. 27, 2019.

[3] C. Seyfried, H. Palko, and L. Dubbs, "Potential local environmental impacts of salinity gradient energy: A review," *Renew. Sustain. Energy Rev.*, vol. 102, pp. 111–120, 2019.

[4] S. J. Kim, S. K. Kim, and J. C. Park, "The corrosion and mechanical properties of Al alloy 5083-H116 in metal inert gas welding based on slow strain rate test," *Surf. Coatings Technol.*, vol. 205, no. SUPPL. 1, pp. S73–S78, 2010.

[5] Kiryanto, A. Firdhaus, U. Budiarto, E. S. Hadi, and M. H. Al Ihsan, "the Impact of Post-Weld Heat Treatment on Re-Welding in Shielded Metal Arc Welding Joint St42 Steel," *J. Teknol.*, vol. 86, no. 6, pp. 21–27, 2024.

[6] Y. Qian, Y. Li, S. Jungwirth, N. Seely, Y. Fang, and X. Shi, "The application of anti-corrosion coating for preserving the value of equipment asset in chloride-laden environments: a review," *Int. J. Electrochem. Sci.*, vol. 10, no. 12, pp. 10756–10780, 2015.

[7] S. I. Bhat, M. Mobin, S. Islam, S. Zehra, and Shahid-ul-Islam, "Recent advances in anticorrosive coatings based on sustainable polymers: Challenges and perspectives," *Surf. Coatings Technol.*, vol. 480, p. 130596, 2024.

[8] H. B. Putra, J. A. Affi, G. Gunawarman, and Y. Yetri, "Pemanfaatan Ekstrak Kulit Kakao Sebagai Aditif Cat Untuk Pengendalian Laju Korosi Pada Paku Konstruksi Kapal Kayu," *INOVTEK POLBENG*, vol. 8, no. 1, pp. 52–57, 2018.

[9] E. Supraptiah, M. Taufik, and R. F. Azzahrah, "PEMANFAATAN SERAT DAUN NANAS MENJADI FILLER PADA PEMBUATAN CAT RAMAH LINGKUNGAN," *KINETIKA*, vol. 13, no. 02, pp. 7–11, 2022.

[10] Ł. Kampa, Ł. Sadowski, and A. Królicka, "The use of synthetic and natural fibers in epoxy coatings: A comparative mechanical and economic analysis," *Int. J. Adhes. Adhes.*, vol. 117, p. 103017, 2022.

[11] L. Simatupang *et al.*, "Kinerja Ratio Silika-Cat Dengan Metode Dipcoating Pada Permukaan Logam Untuk Penghambat Laju Korosi," *J. Sci. Appl. Technol.*, vol. 7, no. 1, pp. 43–51, 2023.

[12] V. Panaite, V. MUSAT, S. BOICIUC, G. G. Istrate, and R. Tamara, "Effect of ZrO_2 Nanoparticles on the Mechanical and Anticorrosion Properties of epoxy Coating," *Ann. "Dunarea Jos" Univ. Galati. Fascicle IX, Metall. Mater. Sci.*, vol. 36, no. 2, pp. 44–48, 2013.

[13] W. Xu, Z. Wang, E.-H. Han, S. Wang, and Q. Liu, "Corrosion performance of nano-ZrO_2 modified coatings in hot mixed acid solutions," *Materials (Basel).*, vol. 11, no. 6, p. 934, 2018.

[14] S. Shi, Z. Zhang, and L. Yu, "Hydrophobic polyaniline/modified SiO_2 coatings for anticorrosion protection," *Synth. Met.*, vol. 233, pp. 94–100, 2017.

[15] V. S. Sumi *et al.*, "PANI-Fe_2O_3 composite for enhancement of active life of alkyd resin coating for corrosion protection of steel," *Mater. Chem. Phys.*, vol. 247, p. 122881, 2020.

[16] F. C. P. Masim *et al.*, "Synergistic effect of PANI–ZrO_2 composite as antibacterial, anti-corrosion, and phosphate adsorbent material: synthesis, characterization and applications," *Environ. Technol.*, vol. 40, no. 2, pp. 226–238, 2019.

[17] N. Nadliriyah, A. L. Putri, and T. Triwikantoro, "PANi/ZrO_2-composite coating for corrosion protection in 3.5 M NaCl solution," in *IOP Conference Series: Materials Science and Engineering*, 2019, vol. 496, no. 1, p. 12059.

[18] S. Zor and B. Budak, "Photocatalytic degradation of congo red by using PANI and PANI/ZrO_2: under UV-A light irradiation and dark environment," *Desalin. Water Treat.*, vol. 201, pp. 420–430, 2020.

[19] F. Tikhani *et al.*, "Polyurethane/silane-functionalized ZrO_2 nanocomposite powder coatings: Thermal degradation kinetics," *Coatings*, vol. 10, no. 4, p. 413, 2020.

[20] H. Huang, Z. C. Guo, W. Zhu, and F. C. Li, "Preparation and characterization of conductive polyaniline/zirconia nanoparticles composites," *Adv. Mater. Res.*, vol. 221, pp. 302–307, 2011.

[21] N. Nadliriyah, A. L. Putri, and T. Triwikantoro, "PANi/ZrO_2-composite coating for corrosion protection in 3.5 M NaCl solution," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 496, no. 1, 2019.

[22] S. Kasisomayajula, N. Jadhav, and V. J. Gelling, "Recent Advances in Polymer Nanocomposite Coatings for Corrosion Protection," *Adv. Nanostructured Compos.*, pp. 241–277, 2019.

[23] M. Zainuri, "Structures and electric properties of PANI/polymorphic-ZrO_2 composites," *RSC Adv.*, vol. 13, no. 15, pp. 10414–10423, 2023.

[24] H. Wang, J. Lin, and Z. X. Shen, "Polyaniline (PANi) based electrode materials for energy storage and conversion," *J. Sci. Adv. Mater. devices*, vol. 1, no. 3, pp. 225–255, 2016.

[25] X. Song *et al.*, "Thermophysical and mechanical properties of cubic, tetragonal and monoclinic ZrO_2," *J. Mater. Res. Technol.*, vol. 23, pp. 648–655, 2023.

[26] K. M. Shwetha, B. M. Praveen, and B. K. Devendra, "A review on corrosion inhibitors: types, mechanisms, electrochemical analysis, corrosion rate and efficiency of corrosion inhibitors on mild steel in an acidic environment," *Results in Surfaces and Interfaces*, p. 100258, 2024.

[27] R. J. D. Tilley, *Crystals and crystal structures*. John Wiley & Sons, 2020.

[28] M. M. Kržmanc, B. Jančar, H. Uršič, M. Tramšek, and D. Suvorov, "Tailoring the shape, size, crystal structure, and preferential growth orientation of $BaTiO_3$ plates synthesized through a topochemical conversion process,"*Cryst. Growth Des.*,vol.17,no.6, pp. 3210, 2017.