Jurnal Riset Kimia
ISSN (print) : 1978-628X
ISSN (online) : 2476-8960

Corrosion Analysis on Stainless Steel (SS304) Using A Coating Method Based On Silica from Natural Sand of Hukurila Village

Stevi Silahooy[1*], Geovanny Branchiny Imasuly[1], Wilma Latuny[2], Delpina Nggolaon[3]
[1]Department of Petroleum Engineering, Faculty of Engineering, Pattimura University, Indonesia
[2]Department of Industrial Engineering, Faculty of Engineering, Pattimura University, Indonesia
[3]Department of Chemical Engineering, Faculty of Engineering, Pattimura University, Indonesia

Corresponding Author:
Stevi Silahooy
silahooystevi@gmail.com

Received: December 2024
Accepted: September 2025
Published: September 2025

Abstract

Corrosion analysis was performed on stainless steel (SS304) coated with silica extracted from silica sand in Hukurila Village using the coprecipitation method. The XRF results showed an increase in silica content from 58.118% to 81.247%, indicating high purity. XRD testing revealed that the silica was amorphous, while SEM analysis showed that the silica powder particles were irregular in shape and size, and tended to undergo agglomeration. The silica was then applied as a coating on SS304 using Nippon Paint with silica-to-paint weight ratios of 95:5, 90:10, and 80:20. The samples were tested in a 3.5% NaCl solution for 7 days using polarization methods on a potentiostat to measure corrosion resistance. The results showed that the 80:20 weight ratio provided the highest improvement in corrosion resistance. This enhancement is attributed to the more compact and uniform coating structure formed at higher silica loading, which effectively minimizes micro-pores, strengthens the barrier effect, and suppresses localized pitting corrosion.

Keywords: *coprecipitation; silica powder; coating; corrosion rate.*

Introduction

Steel is one of the metals that is highly sought after in the oil and gas industry [1],[2]. One of its applications is in the manufacture of oil and gas production well casings. A casing is a steel pipe that serves to prevent the collapse of the well walls, seal abnormal pressure zones, loss zones, and so on. In the development of drilling technology, casing wear must be taken seriously because it can lead to significant economic losses [3]. In this era, the oil and gas industry is facing a significant issue: casing leaks caused by corrosion, which affects the production process of crude oil and natural gas [4]–[6]. The corrosion that occurs on casings varies, including: uniform corrosion, pitting corrosion, erosion corrosion, galvanic corrosion, stress corrosion, crevice corrosion, microbiological corrosion, and fatigue corrosion (Novita et al.; Utomo). According to research by the National Association of Corrosion Engineers (NACE), it is estimated that the annual cost of repairing damage caused by corrosion in the United States amounts to $276 billion or approximately 4.278 trillion rupiah [4]. The International Measures for the Prevention, Application, and Economics of Corrosion Technologies (IMPACT) study report recorded that in 2016, the global annual cost of corrosion reached around USD 2.5 trillion [7]. In Indonesia, the economic loss due to corrosion amounts to 1 - 1.5% of GDP (Gross Domestic Product) or trillions of rupiah [8]. This makes corrosion not only a technical challenge but also a national economic concern.

To mitigate this issue, coating methods have been widely applied as a corrosion protection strategy [6],[9]–[11]. While effective to some extent, conventional coatings particularly polymer-based tend to be porous, exhibit weak adhesion, and degrade under thermal or chemical stress, which limits their long-term performance. Thus, more economical yet durable alternatives are needed to enhance the corrosion resistance of commercial steels such as stainless steel 304 (SS304), which is commonly used in construction, chemical industries, infrastructure, and oil and gas facilities. Despite its inherent corrosion resistance, SS304 remains vulnerable in aggressive environments [12].

One promising approach is the incorporation of silica (SiO_2) into coatings. Silica particles reduce porosity, improve adhesion, enhance mechanical strength, and increase resistance to thermal and chemical degradation. Recently, silica has been successfully synthesized from natural materials such as sand, offering lower production costs while maintaining high purity [13]–[16]. Hukurila Village in Maluku, for example, has abundant sand resources containing 50–58 wt.% silica, which can be extracted into amorphous silica using the co-precipitation method. This method is simple, cost-effective, and capable of producing fine particles [17]–[19]. Building upon this, the present study aims to analyze the corrosion resistance of SS304 coated with silica derived from Hukurila sand, offering a potentially more effective and economical protection strategy compared to conventional polymer coatings.

Experimental

Equipment

The equipment used in this study consisted of standard laboratory equipment and advanced analytical instruments. Basic equipment included mortars, measuring cylinders, pH paper, dropper pipettes, 25 mL volumetric pipettes, magnetic stirrers, petri dishes, volumetric flasks, Erlenmeyer flasks, stir bars, sieves, filter paper, stopwatches, digital balances, paint stir sticks, and 3.5% NaCl solution. For further characterization, X-Ray Fluorescence (XRF) analysis was performed using a Malvern Panalytical Zetium spectrometer, while X-Ray Diffraction (XRD) was performed with a Rigaku Miniflex 600 diffractometer. Microstructural characterization was performed using a Scanning Electron Microscope (SEM) available at the Sepuluh Nopember Institute of Technology (ITS) research facility. Electrochemical corrosion tests were also conducted at ITS using a potentiostat in their electrochemistry and corrosion laboratory of the Chemical Engineering Department, although the specific potentiostat brand/model could not be confirmed.

Material

The materials used in this study were natural sand, $AgNO_3$, HCl, NaOH, Nippon Paint, and distilled water (aquadest).

Methods

Silica (SiO_2) Synthesis

The first stage is the identification of the chemical element content in the beach sand from Hukurila Village, Ambon City. The next stage is the purification process of the sand to remove impurities in order to obtain high-purity amorphous silica. The synthesis of amorphous silica is carried out using the co-precipitation method.

Silica (SiO_2) Characterization

The characterization instruments used include: 1) X-Ray Fluorescence (XRF), 2) X-Ray Diffraction (XRD), and 3) Scanning Electron Microscope (SEM). XRF characterization is performed to determine the composition of the sand and silica powder. XRD characterization is conducted to identify the structure and phase of the silica powder, performed at a 2θ angle range of 0° to 90°. Meanwhile, the microstructure, shape, and particle size characterization are carried out using the SEM instrument with a magnification of 500x.

Silica Coating on Production Casing (SS304)

The silica paint mixture was stirred using a magnetic stirrer at a speed of approximately 700 rpm (stirrer setting 7) for 10 minutes to ensure proper dispersion of silica within the paint matrix. Homogeneity was confirmed visually by the absence of agglomerates, the uniform distribution of color, and the consistent viscosity of the paint mixture before application onto the substrate.

DOI: https://doi.org/10.25077/jrk.v16i2.808

Corrosion Resistance Testing

Corrosion resistance testing was carried out using a potentiostat with a conventional three-electrode system, consisting of stainless steel 304 (SS304) as the working electrode (WE), Ag/AgCl as the reference electrode (RE), and stainless steel as the counter electrode (CE). The test was performed in a 3.5% NaCl solution at room temperature (±27 °C) to simulate a marine environment. The potential was scanned within the range of –1.5 V to +1.5 V with a scan rate of 1 mV/s. The obtained polarization curves were then analyzed using the Tafel extrapolation method through Anova software version 1.8, which is commonly used in electrochemical research. This analysis provided electrochemical parameters such as the Tafel constants (b_a, b_c), corrosion potential ($E_{corr,cal}$; $E_{corr,obs}$), corrosion current density (J_{corr}, mA/cm^2), corrosion current (I_{corr}, mA), corrosion rate (CR, mpy), polarization resistance (Rp, Ω), and testing potentials (E_{begin}, E_{end}).

Results and Disscusion

Geology of the Sample Collection

The sample collection site is located in Hukurila, Leitimur Selatan District, Ambon City, with coordinates 128°14'14.217" East and 3°44'35.788" South. According to the regional geological map of the Ambon sheet (Figure 1), the sample collection area is part of the Ambon Granite Intrusion (marked in red on the map). This granite rock formation dates back to the Pliocene epoch, approximately 4 million years ago [20].

The granite rock is characterized by a white to grayish color, holocrystalline crystallinity, phaneritic texture, with coarse to medium grain size and euhedral-subhedral crystal forms. The main constituent minerals are quartz, feldspar, biotite, plagioclase, and hornblende. The sample collected is beach sand, primarily composed of quartz. The quartz sand was taken near the granite outcrop (Figure 2). Based on its similar characteristics, this beach sand is identified as quartz sand, which originates from the weathering of granite rocks exposed in the study area.

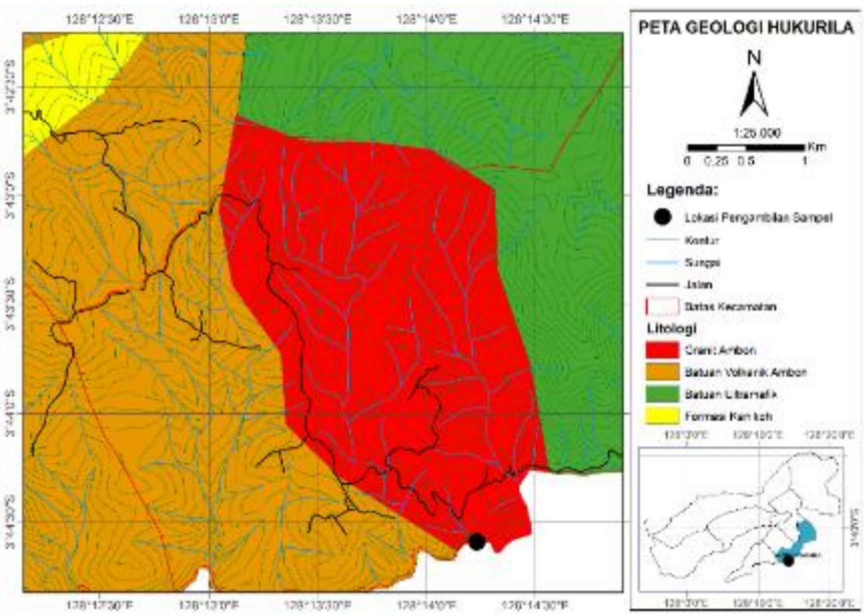


Figure 1. Geological Map of Hukurila Village.

Figure 2. Granite Outcrop at the Sample Collection Site.

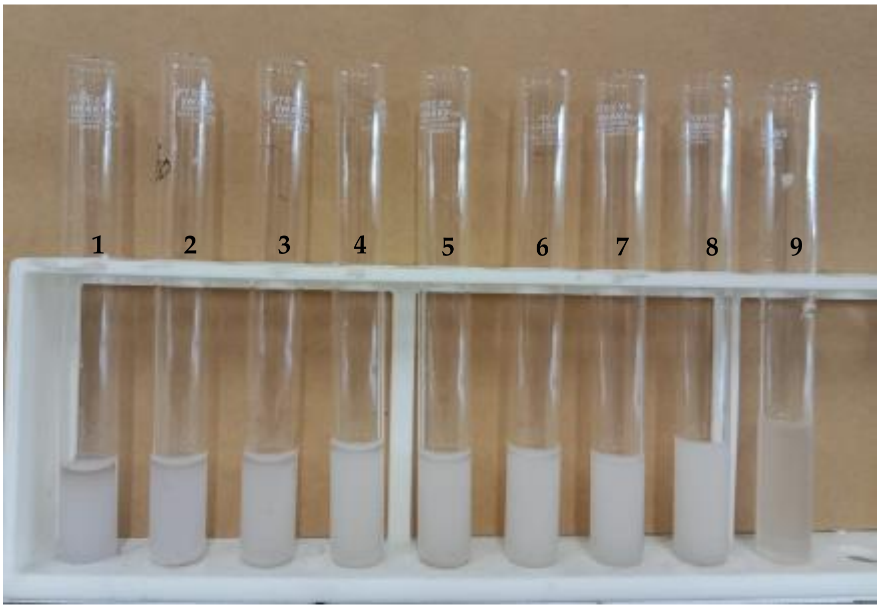


Figure 3. Testing the Salt Content Attached to the Sand Using $AgNO_3$ Solution.

Sample Preparation

The sand sample collected from the beach of Hukurila Village, Ambon City, underwent a washing process 9 times to remove the salt content attached to the sand.

The salt content testing was performed using a silver nitrate ($AgNO_3$) solution with the argentometric method, as shown in Figure 3. In this method, the $AgNO_3$ solution acts as the titrant, reacting with chloride ions (Cl^-) present in the salt. The reaction between $AgNO_3$ and Cl^- produces a white precipitate of AgCl (silver chloride) [21].

In the 9th washing, no white precipitate was observed after the addition of $AgNO_3$ solution, indicating that the salt content had been successfully removed from the sand sample. The cleaned sand was then dried and ground using a mortar, and sieved through a 100-mesh sieve as shown in Figure 3. From this sieving, 12 grams of sand were taken for XRF testing to determine the elemental composition. Additionally, 100 grams of the sand were

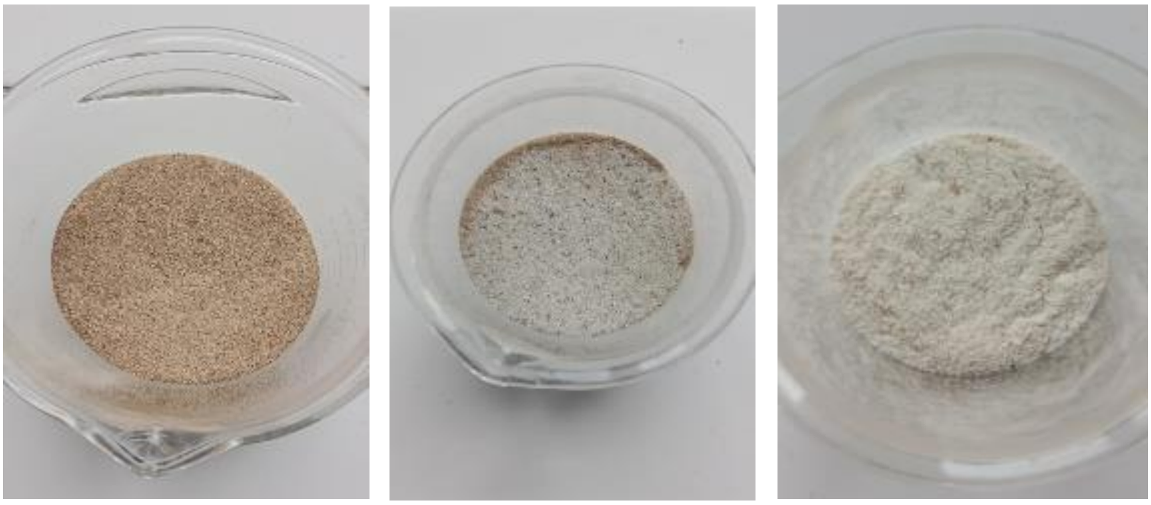
 DOI: https://doi.org/10.25077/jrk.v16i2.808

prepared for the leaching extraction process using a 2M HCl solution of 1000 mL, with a 1:10 ratio. This process aims to extract or separate certain compounds from the solid material, specifically to separate the Fe compounds contained in the sand.

XRF Analysis

The beach sand from Hukurila is naturally rich in silica (SiO_2), as indicated by the silicon (Si) element percentage of 58.118%. The largest minor elements are aluminum (Al) and potassium (K), with each element having a percentage of 12.109% and 10.419%, respectively. Naturally, the Hukurila sand has a milk-brown color, as shown in Figure 4a, indicating the presence of many organic impurities. After the purification process using HCl (leaching) (Figure 4b), it is observed that the sand color changed to white with slight traces of milk-brown and black. This change indicates that, although some impurities remain, the silicon (Si) content has increased. This is confirmed by the whiter appearance of the sand, showing an enhancement in the silica (SiO_2) compound content [22].

To enhance the silica to high purity, purification was carried out using the co-precipitation method, which transforms silica sand into silica powder (Figure 4c) [23]. This process successfully increased the silica percentage in the sand sample significantly, from 58.118% to 81.274% (Table 1). This demonstrates the effectiveness of the co-precipitation method in improving silica purity.



(a) (b) (c)

Figure 4. Sample Appearance: a) Initial Silica Sand b) Leached Silica Sand c) Co-precipitated Silica Sand.

Table 1. Elemental Composition of Sand and Silica Powder.

Element	Sand	Silica Powder
Si	58.118%	81.247%
Al	12.109%	8.361%
K	10.419%	7.192%
Lain-lain	2.240%	3.200%

XRD Analysis

The XRD (X-Ray Diffraction) test results of the silica powder show that the SiO_2 phase formed is amorphous, indicated by the absence of crystalline phase peaks in the diffractogram and the presence of only a single peak at a 2θ angle of 21.6° (Figure 5). This is confirmed by the study conducted by Munasir et al., which states that the amorphous phase forms at this angle [16].

Figure 5 shows that the washing process of salt (NaCl) from the reaction between HCl (strong acid) and NaOH (strong base) has been successfully carried out. This is indicated by the absence of NaCl peaks in the X-ray diffraction pattern.

SEM Analysis

The SEM testing was conducted to analyze the morphology and structure of the silica powder (Figure 6) and the surface of SS304 metal in a corrosive environment (Figure 7) [24].

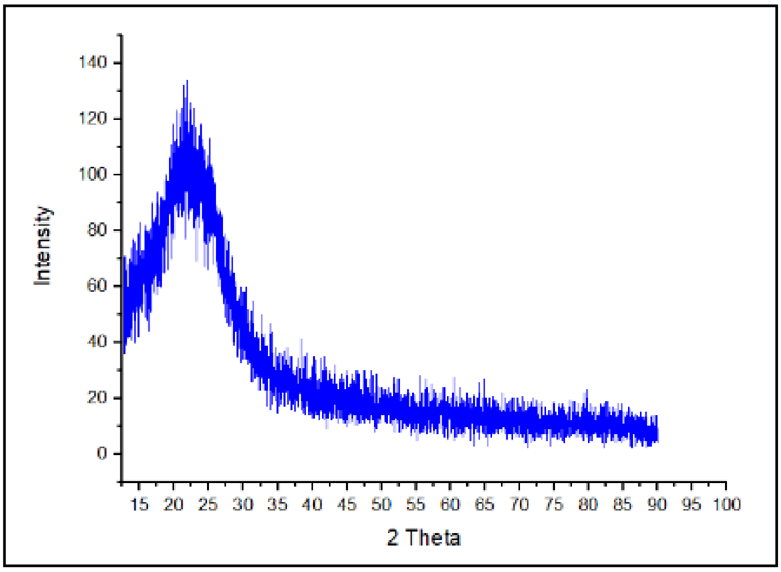


Figure 5. X-Ray Diffraction Pattern of Silica Powder.

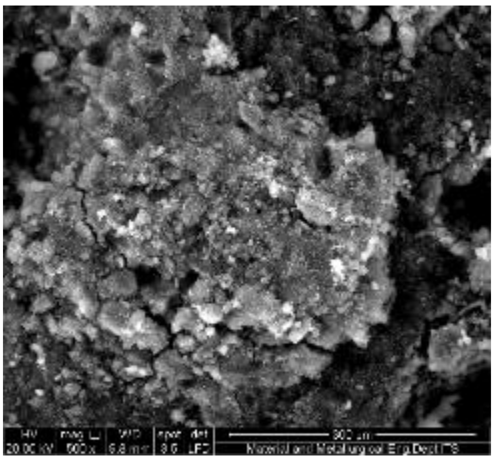
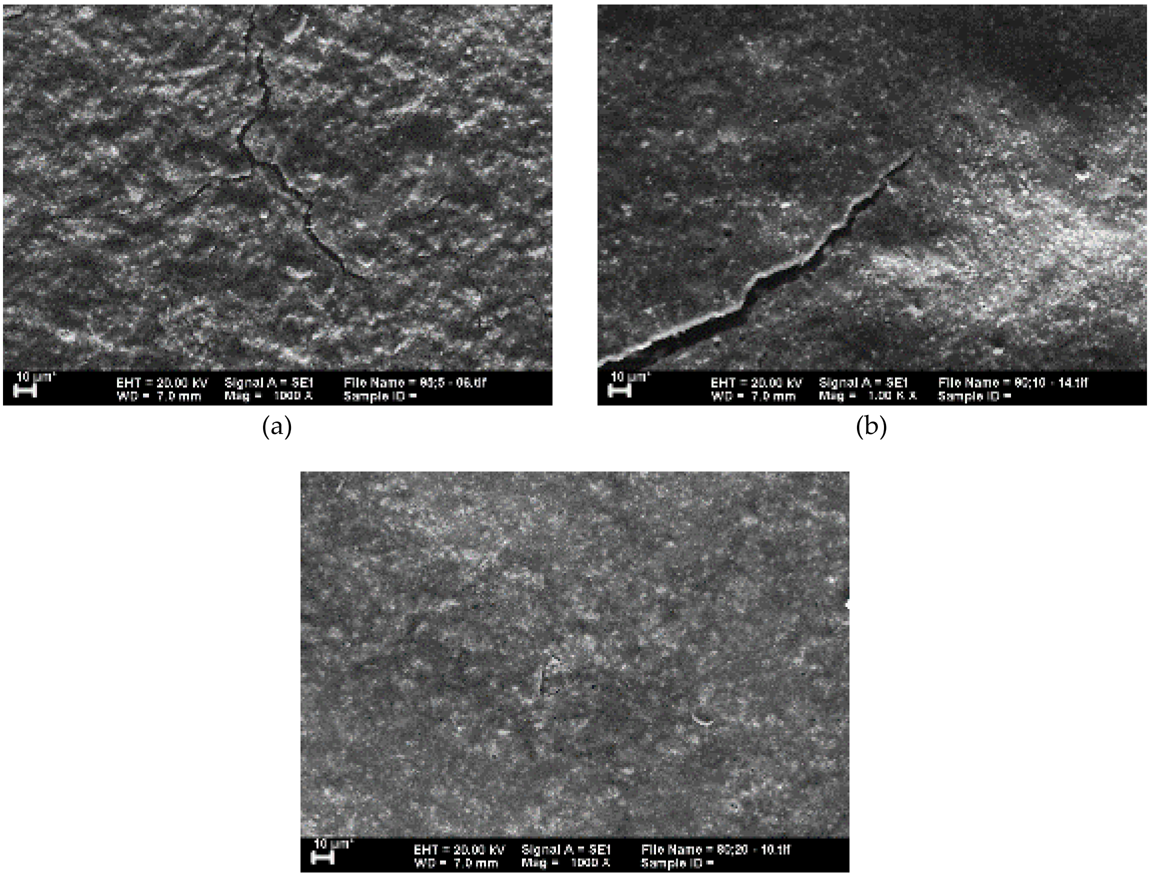


Figure 6. SEM Image of Silica Powder at 500x Magnification.

DOI: https://doi.org/10.25077/jrk.v16i2.808



(a) (b) (c)

Figure 7. SEM Images of Steel Surface in a Corrosive Environment Coated with Silica Powder + Paint at Ratios of a) 95:5 b) 90:10 c) 80:20.

The SEM image of silica powder (Figure 6) shows that the particle size of the silica powder is not uniform and tends to undergo agglomeration[25]. Meanwhile, based on the SEM images of the SS304 metal surface in a corrosive environment (Figure 7), it can be seen that the addition of 20% silica into the paint significantly improves the corrosion resistance of SS304 steel. This improvement is attributed to the formation of a more compact and stable protective layer, where silica particles act as physical barriers that hinder the penetration of aggressive chloride ions into the stainless steel substrate. As a result, the passive oxide film (Cr_2O_3) is better maintained, and the initiation and propagation of pitting corrosion are considerably suppressed. This observation aligns with findings in the literature, where silica-based coatingssuch as sol gel silica films have demonstrated an order of magnitude increase in polarization resistance (Rp), indicating enhanced corrosion barrier performance [26]. Moreover, studies on hybrid organic–inorganic coatings containing silica nanofillers report increased hydrophobicity, reduced porosity, and lowered corrosion current density (Icorr), all contributing to improved protection against localized corrosion [27].

Corrosion Rate Analysis

In this study, corrosion properties were tested using the polarization method to evaluate the corrosion rate of various samples. The test area used had an area of 2 cm^2. Corrosion testing was conducted in a 3.5% NaCl corrosive solution using a potentiostat, and the data were analyzed in the form of linear polarization graphs (Figure 8). The polarization curves for each sample, including SS304, SS304 + paint, SS304 + paint + SiO_2 5%, SS304 + paint + SiO_2 10%, and SS304 + paint + SiO_2 20%, can be seen in Figure 9. Information regarding the corrosion rate for each sample is detailed in Table 2.

Figure 8. Corrosion Rate Testing Using a Potentiostat.

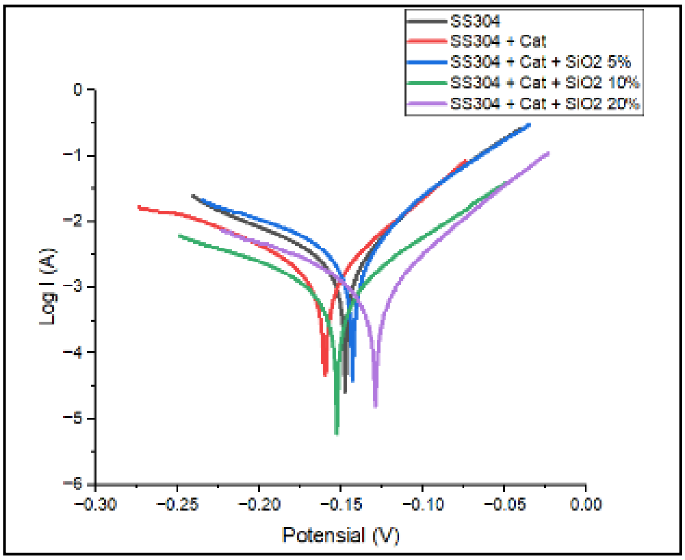


Figure 9. Polarization Test Curve of Samples.

Table 2. Corrosion Rate of Samples Using Polarization Test.

No.	**Sample**	**Corrosion Rate (mmpy)**
1	SS304 murni	0.0301
2	SS304 + cat	0.0225
3	SS304 + cat + SiO_2 5%	0.0530
4	SS304 + cat + SiO_2 10%	0.0121
5	SS304 + cat + SiO_2 20%	0.0114

 DOI: https://doi.org/10.25077/jrk.v16i2.808

The polarization test results (Table 2) demonstrate that the addition of 5% SiO_2 unexpectedly decreases the corrosion resistance of SS304 compared to bare SS304 and paint-only coatings. This reduction is mainly attributed to poor dispersion of silica particles at low concentrations, which can cause particle agglomeration and create localized defects or micro-pores within the coating matrix. These defects facilitate the penetration of chloride ions into the steel surface, thus accelerating corrosion instead of preventing it. In contrast, at higher loadings of 10% and 20% SiO_2, the coating exhibits a more compact and uniform structure, which effectively blocks the diffusion of aggressive species and reinforces the passive Cr_2O_3 layer on stainless steel. This barrier effect significantly improves the corrosion resistance, as reflected in the lower corrosion rates of 0.0121 mmpy and 0.0114 mmpy, respectively. Similar findings have been reported in previous studies, where optimally dispersed SiO_2 nanoparticles were shown to enhance coating compactness and reduce corrosion current density, thereby suppressing localized pitting corrosion [28].

Conclusions

Based on the research results, it can be concluded that coating stainless steel (SS304) with silica powder extracted from silica sand using the co-precipitation method significantly improves corrosion resistance.

Acknowledments

The author would like to express gratitude to the head of the Chemistry Laboratory, Faculty of MIPA, Pattimura University, for providing support in the form of laboratory space, as well as equipment and materials for the implementation of this research.

References

1. Goren, A. Y., Dincer, I., Gogoi, S. B., Boral, P. & Patel, D., Recent developments on carbon neutrality through carbon dioxide capture and utilization with clean hydrogen for production of alternative fuels for smart cities. *Int. J. Hydrogen Energy*, **79(July)**: 551–578 (2024).
2. Pauliuk, S., Wang, T. & Müller, D. B., Steel all over the world: Estimating in-use stocks of iron for 200 countries. *Resour. Conserv. Recycl.*, **71**: 22–30 (2013).
3. Jin, C., Qian, F. & Feng, F., Effect of variable drill pipe sizes on casing wear collapse strength. *J. Pet. Sci. Eng.*, **195(December 2019)**: 107856 (2020).
4. Li, L., Hubler, M. H. & Xi, Y., Modeling the corrosion of steel casing and the damage of well cement in a borehole system. *Constr. Build. Mater.*, **259**: 1–23 (2020).
5. Mubarak, G., Verma, C., Barsoum, I., Alfantazi, A. & Rhee, K. Y., Internal corrosion in oil and gas wells during casings and tubing: Challenges and opportunities of corrosion inhibitors. *J. Taiwan Inst. Chem. Eng.*, **150(September)**: 1–8 (2023).
6. Jiang, C. yin., Liu, X. zhou., Li, X. juan., Fu, G. wei., Zhang, K. li., Wang, J. & Xie, C. dong., Preparation and anti-corrosion performance of temperature-resistant selfhealing coating for L80 Pipe. *Int. J. Electrochem. Sci.*, **18(4)**: 100041 (2023).
7. Santos, L. R. L., Marino, C. E. B. & Riegel-Vidotti, I. C., Silica/chitosan hybrid particles for smart release of the corrosion inhibitor benzotriazole. *Eur. Polym. J.*, **115(June)**: 86–98 (2019).
8. Pramana, A. A. & Fadillah, Y. R., Analysis of Corrosion in Production Tubing Using Olga Simulator. *PETRO Jurnal Ilm. Tek. Perminyakan*, **11(2)**: 47–51 (2022).
9. Niu, L. & Cheng, Y. F., Development of innovative coating technology for pipeline operation crossing the permafrost terrain. *Constr. Build. Mater.*, **22(4)**: 417–422 (2008).
10. Senna, C. M., Oliveira, V. L. de C., Santos, D., Pessotti de Deus, E., Soares, M. & Miranda, W., Coatings for Saltwater Pipelines. **6495(9)**: 266–272 (2018).
11. Setiawan, A., Kristina Dewi, A. & Mukhlis., Pengaruh Surface Treatment Terhadap Ketahanan Korosi Baja Karbon Tercoating Zinc Fosfat Pada Media Asam Sulfat. *J. Teknol.*, **11(1)**: 57–66 (2019).
12. Riaz, U., Nwaoha, C. & Ashraf, S. M., Recent advances in corrosion protective composite coatings based on conducting polymers and natural resource derived polymers. *Prog. Org. Coatings*, **77(4)**: 743–756 (2014).
13. Rajkumar, R. & Vedhi, C., A study of corrosion protection efficiency of silica nanoparticles acrylic coated on mild steel electrode. *Vacuum*, **161(October 2018)**: 1–4 (2019).

14. Arief, H., Pramudita, M. & Pitaloka, A. B., Synergistic Ability of Tannin – Silica as a Corrosion Inhibitor with the Addition of KI to Mild Steel in Demineralized Water. *World Chem. Eng. J.*, **7(1)**: 11 (2023).
15. Munasir., Triwikantoro., Zainuri, M. & Darminto., Synthesis of SiO_2 nanopowders containing quartz and cristobalite phases from silica sands. *Mater. Sci. Pol.*, **33(1)**: 47–55 (2015).
16. Munasir., Rohmawati, L., Taufiq, A. & Darminto., Amorphous SiO_2 Nanoparticles from Natural Sands: Structure and Porosity. *C. J Nat Sci*, **19(3)**: 563–579 (2020).
17. Taufiq, A., Nikmah, A., Hidayat, A., Sunaryono, S., Mufti, N., Hidayat, N. & Susanto, H., Synthesis of magnetite/silica nanocomposites from natural sand to create a drug delivery vehicle. *Heliyon*, **6(4)**: (2020).
18. Saragi, T., Permana, B., Saputri, M., Safriani, L., Rahayu, I. & Risdiana, R., Sintesis Nanopartikel Magnetik Dengan Metode Kopresipitasi. *J. Mater. dan Energi Indones.*, **7(02)**: 17 (2018).
19. -, M., Shofiah, S. & Suharyadi, E., Sintesis Nanopartikel Nickel Ferrite ($NiFe_2O_4$) dengan Metode Kopresipitasi dan Karakterisasi Sifat Kemagnetannya (Halaman 20 s.d. 25). *J. Fis. Indones.*, **19(56)**: 20–25 (2015).
20. Tjokrosapoetro, S, Achdan, A, Suwitodirdjo, S, Rusmana, E, Abidin, H. ., Peta Geologi Lembar Masohi Skala 1:250.000. *Pus. Penelit. dan Pengemb. Geol.*, (1993).
21. Umaminingrum, M. T. & Purwaningtyas, F. Y., Validasi metode analisa penetapan kadar ammonium klorida di PT. Novapharin Pharmaceutical Industries. *J. Integr. Proses dan Lingkung.*, **1(1)**: 18–23 (2023).
22. Khalifa, M., Hajji, M. & Ezzaouia, H., Impurity removal process for high-purity silica production by acid leaching. *EPJ Web Conf.*, **29**: 2–5 (2012).
23. Hasanah, M., Sembiring, T., Sebayang, K., Humaidi, S., Rahmadsyah., Saktisahdan, T. J., Handoko, F., *et al.*, Extraction Of Silica Dioxide (SiO2) From Mount Sinabung Volcanic Ash with Coprecipitation Method. *IOP Conf. Ser. Mater. Sci. Eng.*, **1156**: 1–5 (2021).
24. Aisyah, N., Rifai, H., Maisonneuve, C. B. D. La., Oalmann, J., Forni, F., Eisele, S., Phua, M., *et al.*, Scanning electron microscope (SEM) imaging and analysis of magnetic minerals of lake Diatas peatland section DD REP B 693. *J. Phys. Conf. Ser.*, **1481(1)**: (2020).
25. Silahooy, S., Analisis Serbuk Silika Amorf (SiO_2) Berbahan Dasar Pasir. *Scie Map J*, **2(2)**: 75–78 (2020).
26. Gąsiorek, J., Gąsiorek, A., Babiarczuk, B., Jones, W., Simka, W., Detyna, J., Kaleta, J., *et al.*, Anticorrosion properties of silica-based sol-gel coatings on steel – The influence of hydrolysis and condensation conditions. *Ceram. Int.*, **48(24)**: 37150–37163 (2022).
27. Pourhashem, S., Saba, F., Duan, J., Rashidi, A., Guan, F., Nezhad, E. G. & Hou, B., Polymer/Inorganic nanocomposite coatings with superior corrosion protection performance: A review. *J. Ind. Eng. Chem.*, **88**: 29–57 (2020).
28. Samad, U. A., Alam, M. A., Abdo, H. S., Anis, A. & Al-Zahrani, S. M., Synergistic Effect of Nanoparticles: Enhanced Mechanical and Corrosion Protection Properties of Epoxy Coatings Incorporated with SiO_2 and ZrO_2. *Polymers (Basel).*, **15(14)**: (2023).