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CORROSION PROTECTION ABILITY OF POLYPYRROLE COATED MILD STEEL IN BURIED SAND

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ABSTRACT

Corrosion prevention is a global issue. One way to reduce metal corrosion is by applying polymer coatings. Corrosion prevention increasingly involves the use of polypyrrole (PPy) coatings, which significantly reduce corrosion rates and provide anodic protection. The purpose of this study was to deposit PPy on mild steel (MS) from 0.4 M pyrrole in 0.1 M sodium potassium (Na-K tartrate) by cyclic voltammetry (CV). This study employed electrodeposition of PPy on MS by CV and explored its corrosion protection performance in the buried sand medium containing 0.1 M NaCl and 0.1 M H_2SO_4 *by the potentiodynamic polarization (PDP) method. The results revealed that with an increase in the number of cycles, the CV showed that the PPy layer formed gradually and covered the MS surface. The oxidation peak vanished after the first cycle, and the current increased with the increasing cycles. The synthesized PPy coating was analyzed by a scanning electron microscope (SEM), which revealed a compact coating layer with cauliflower-like morphology. It was also examined using an energy-dispersive X-ray spectrometer (EDX), which confirmed the presence of carbon, nitrogen, and oxygen elements. The open-circuit potential (OCP) remained constant over time, resulting in a stable film. The corrosion potential also showed a slight change compared to both media. The significant findings of this study were that the PPy coating behaved as a mixed inhibitor in both media, and the corrosion inhibition efficacy of the PPy coating was approximately 99% in* H_2SO_4 *and 98% in NaCl, with good adhesion.*

INTRODUCTION

Polypyrrole (PPy) is a fascinating conductive polymer for various reasons, even though polyaniline has received the most attention (Stejskal, 2015). It has a conductivity of around 100 S cm^{-1} (W. Li, 2018) in its nanotube form. This is claimed to be one of the highest conductivity values among conducting polymer powders, including polyaniline and poly(3,4-ethylenedioxythiophene) (Zhao et al., 2022).

The PPy nanotube sustains its conductivity in neutral and alkaline conditions. Therefore, it is utilized in energy conversion and energy-storage devices, as well as for corrosion protection, among other applications, due to its strong electrical conductivity, effective physical shielding, and wide range of functionalization options. Surface coating is a characteristic alteration technique used to produce a compact layer on the metal surface. A polymer coating is one technique used to mitigate metal corrosion (He et al., 2024). Currently, the application of PPy coatings is effective in preventing corrosion, acting as an anodic protection and substantially reducing corrosion rates (Dalmoro et al., 2019; Hammache et al., 2003). Electropolymerization of PPy onto metal surfaces offers several advantages, including the use of a relatively straightforward electrochemical procedure that employs both galvanostatic and potentiostatic methods. The resulting coating exhibits excellent mechanical properties and very high adhesion. It exhibits strong conductivity over a wide pH range and high thermal stability (up to 150°C in air). Aguiar et al. (2023) conveyed that the electrochemically synthesized

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PPy with outstanding corrosion protection properties was possible due to the excellent electronic conductivity of PPy (1 Scm^{-2}) (Aguiar et al., 2023; Lin et al., 2025).

PPy has been mostly electro-synthesized onto metals such as iron, mild steel (MS), and stainless steel (SS), using oxalic acid (Alsingery, 2017; Beck et al., 1994). Su and Iroh (Iroh & Su, 2000; Iroh & Wood, 1996) found that the reduction of the pH of oxalic acid enhanced the adherence of PPy to the metal surface. Polymer films prepared from extremely acidic solutions are coarse and turbid; however, alkaline solutions can be used to produce thin films. Sodium sulphate (Troch-Nagels et al., 1992), benzenesulphonate (Iroh & Su, 2000), sodium salicylate, and Hydrochloric acid were reported as supporting electrolytes (Alsingery, 2017; Beck et al., 1994; Chhipa et al., 2024; Hulser & Beck, 1990; Schirmeisen & Beck, 1989). Similarly, Beck et al. (1994) reported the electrochemical polymerization of pyrrole in an oxalic acid solution over an iron surface (Beck et al., 1994; Schirmeisen & Beck, 1989), resulting in poorly adherent PPy. A manganese oxide film was deposited on the metal surface to enhance PPy adhesion by lowering the pH to 1.4 (Jaouhari et al., 2016). De Bruyne et al. (1998) achieved successful results (De Bruyne et al., 1998). Ferreira et al. showed that a 10% aqueous nitric acid treatment inhibited iron dissolution while enabling pyrrole oxidation to proceed (Ferreira et al., 1990). Depositing polypyrrole on iron in oxalic acid yields smooth PPy layers, exhibiting good corrosion resistance but poor adhesion (Beck et al., 1994; Rahman & Ba-Shammakh, 2004). The camphor sulfonic acid-doped conducting PPy on 304 SS was achieved galvanostatically by X. Jiang et al. (2017) and L. Jiang et al. (2017). It was found that a PPy camphorsulfonic acid coating exhibits low contact resistance and provides robust corrosion protection over a prolonged period due to its barrier effect and anodic protection. Furthermore, polypyrrole (PPy) was electrosynthesised in the aqueous solution of sodium salicylate by potentiodynamic techniques, like CV and galvanostatic techniques, which showed a better grading of corrosion prevention in salt solution (Jaouhari et al., 2016).

In this paper, we report the electropolymerization of a PPy coating on mild steel (MS) using cyclic voltammetry (CV) with a scan rate of 20 mV/s. The attempt is to improve the corrosion protection performance of PPy coatings on the MS surface. A compact and adherent PPy coating has been achieved using sodium-potassium tartrate (Na-K tartrate) as the electrolyte, resulting in minimal Fe dissolution. The Na-K tartrate exhibits a polarization curve comparable to that of oxalic acid, but it results in an improved PPy coating. The primary purpose is to enhance the PPy layer on MS in an aqueous solution of Na-K tartrate, serving as an electrolyte to improve corrosion inhibition behavior in a buried sand medium.

The study is structured as follows: Section 2 reviews the literature on the polymerization of pyrrole and its corrosion prevention behavior, while Section 3 details the research materials and methods. Section 4 provides the results and discussion, and Section 5 summarizes the study's conclusions and potential future implications.

LITERATURE REVIEW

The use of polymeric compounds as corrosion inhibitors has increased significantly over the last three decades. Conducting polymers, including polythiophene (Pth), polypyrrole (Ppy), and polyaniline (PANI), have opened up new possibilities for the development of corrosion-resistant organic coatings. Polypyrrole (PPy) and polyaniline are the most promising conducting polymers for corrosion protection among those available on the market (Cheung et al., 1988). Polypyrrole (PPy) has been the most studied coating because it requires a slightly neutral pH, which facilitates the discovery of a zinc and iron passivation state (Beck et al., 1994; Hulser & Beck, 1990). In the 19th century, the synthesis of conducting polymers was first reported. In 1979, Diaz et al. reported the first free-standing polypyrrole films synthesized electrochemically (Cheung et al., 1988)**.** Salts such as NBu_4BF_4 or $LiClO_4$ in acetonitrile (with 1% H_2O) were used as the solvent/electrolyte to considerably increase the quality and reversible redox capacity of the polypyrrole layers (Diaz & Castillo, 1980)**.**

Electrochemical deposition is the most effective method for developing conductive polymer coatings due to their limited processability. Coating thickness and shape can be easily controlled by varying potential or current density. It is also a cost-effective method, and can be achieved by using a variety of electrochemical techniques such as potentiostatic, galvanostatic, and cyclic voltammetry (Chhipa et al., 2024; De Bruyne et al., 1998; Hammache et al., 2003). Despite these benefits, because of the high oxidation potential of the monomer, one of the most problematic elements of electrochemical polymerization of pyrrole is the risk of metal dissolution before coating development (X. Li & Zhitomirsky, 2013)

The PPy films on Pt, Au, Ti, and V_2A were synthesized by Schirmeisen and Beck in 1989, but not on iron in an aqueous medium containing several anions such as BF_4^-, ClO_4^-, HSO_4^-, Tos^-, HCO_3^-, H_2PO_4-, HPO_4^{2-}, and $H_2BO_3^-$. It was discovered that well-adhering PPy layers could be obtained when NO_3^- ions were added to the aqueous medium (Schirmeisen & Beck, 1989). Beck et al. (1994) electropolymerized pyrrole on iron in an oxalic medium, but PPy adhesion was poor. To improve PPy adhesion, they employed a previously formed manganese oxide layer on the working surface. By reducing the pH to 1.4, Bruyne et al. achieved successful results (Martins et al., 2009).

The highly adhesive polypyrrole (PPy) films were prepared by electropolymerizing pyrrole on pretreated iron and mild steel. The results showed that a 10% solution of aqueous nitric acid delays iron solubility without halting pyrrole oxidation. In various aqueous conditions comprising Na_2SO_4, $K_2C_2O_4$, or KNO_3, extremely adherent thickness-controlled PPy films were formed under constant current conditions. In the presence of KNO_3, a maximum coulombic efficiency of 95% was achieved at a current density of less than 10 mA/cm2. However, this decreased to 70% and 50% for current densities between 2 and 4 mA/cm², respectively, in the presence of Na_2SO_4 and $K_2C_2O_4$ (Ferreira et al., 1996). The PPy was galvanostatically deposited on iron in aqueous media, and it was revealed that the majority of aqueous electrolytes prevented the deposition of PPy films on iron. However, when oxalic acid and potassium nitrate were used as the electrolyte, polypyrrole coatings were deposited on the iron (Beck et al., 1994; Beck & Oberst, 1987; Schirmeisen & Beck, 1989).

Polypyrrole films were prepared on mild steel using an oxalic acid electrolyte at different temperatures (25-65 °C), current densities (0.5-6.0 mA/cm^2), and pH levels (2.0, 4.0, 7.0, and 8.5). Pyrrole and oxalic acid concentrations were held to 0.1 M each for galvanostatic investigations. The results showed that mild steel was more susceptible to polypyrrole formation in acidic conditions at lower temperatures. When the temperature was higher and the current density was lower, the electrode potentials fluctuated. The worst film quality was observed at pH 7.0, while the most adherent and compact films were formed using an alkaline medium. Higher temperature in an alkaline medium, as opposed to an acidic one, promotes the production of superior polypyrrole films (Rahman & Ba-Shammakh, 2004)

The electrosynthesis of PPy on copper and brass (Cu-Zn alloy) electrodes was accomplished by the anodic oxidation of pyrrole in a sodium tartrate ($C_4H_4Na_2O_6$, 0.2 M) aqueous solution. The tartrate counterions prevent the working electrode from dissolving by inducing pyrrole electropolymerization and creating a passivation layer on its surface. Homogeneous and securely adhering polypyrrole films were electrodeposited on Cu and Cu-Zn alloy electrodes using various electrochemical methods (Bazzaoui et al., 2004). Both aqueous and non-aqueous solutions containing the monomer and a suitable electrolyte serving as dopant or counterion (including organic and inorganic ions) such as oxalate, perchlorate, naphthalenesulfonate, p-toluene sulfonate (pTS), chloride, tetrabutylammonium tetra-fluoroborate (TBAFB), sulfate, styrenesulfonate (SS), and polystyrenesulfonate (PSS) were found to be able to synthesize Polypyrrole (Mollahosseini & Noroozian, 2009).

Polypyrrole sheets were electrosynthesized on 316L stainless steel using near-neutral and alkaline solutions that contained molybdate and nitrate (González & Saidman, 2011). Similarly, polypyrrole was electrochemically prepared on aluminum alloy 37 in the presence of hydroxyquinoline or molybdate anions, and it was reported that the thickness and shape of the electropolymerized polypyrrole had significantly changed (Herrasti et al., 2011). The possibility of improving corrosion resistance by coating buried steel with a polypyrrole (PPy) layer was investigated using potentiostatic methods (El-Shazly & Wazzan, 2012).

Polypyrrole (PPy) composite coatings on carbon steel, utilizing oxalic acid as the electrolyte and phosphotungstic acid (PW12) as the dopant, were developed using cyclic voltammetry. The coatings were more effective at protecting iron than pure PPy. It was demonstrated that the PPy composite covering was more effective at shielding iron than pure PPy. The capacity and potential for corrosion at the open circuit also increased when the pitting attack occurred on the bare substrate (Liu et al., 2017).

Following the passivation process, an inverted-electrode strategy was employed to enhance the poor adhesion and, consequently, the insufficient anticorrosion efficacy of electropolymerized polypyrrole (PPy) on the copper surface. For this, the compact coating (PPy-I) was deposited on the substrate in a cathodic window. When compared to the counterpart made using the conventional method (PPy-T), morphological and physical characterizations showed that PPy-I exerted a satisfactory adhesion strength as well as appropriate thickness and conductivity (X. Zhao et al., 2022)

To prevent corrosion in SAE 1010 carbon steel, polypyrrole/Fe_3O_4 nanoparticles (Fe_3O_4 NPs/PPy) hybrid nanocomposites (HN) were added as anticorrosive additives to an epoxy paint. The electrochemical response of the coated surface with and without HN was analyzed using electrochemical impedance spectroscopy (EIS). It has been demonstrated that, in comparison to the initial epoxy paint made without any corrosion inhibitor, the addition of HN to the epoxy paint may increase the effectiveness of the anticorrosive layer (Aguiar et al., 2023).

For enhanced protection, carbon steel oil pipelines (API X-52) were coated with a polyaniline (PANI)-polypyrrole (PPY) composite using cyclic voltammetry. The effects of several organic and inorganic acids were examined during the electropolymerization of pyrrole and aniline monomers to achieve the optimal coating, as carbon steel is sensitive to acidic solutions. Additional experimental parameters, including substrate concentration, potential window, and potential scan rate, were examined and subsequently refined using a Box-Behnken design (Hamtak et al., 2023). When applied in combination with traditional epoxy novolac resin, epoxidized lignin-based coatings showed enhanced adhesion and corrosion protection, as determined by pull-off adhesion testing and exposure to salt spray, respectively. Furthermore, the significance of size fractionation for achieving uniformity in the final coating formulations was emphasized. High-performing lignin-based anticorrosive coatings could be developed in a promising way (Truncali et al., 2024)

When pyrrole was chemically oxidized with ammonium peroxydisulfate in an aqueous solution, iron microparticles were coated with polypyrrole in situ. A range of hybrid organic/inorganic core-shell materials containing 30–76% iron by weight was created. Scanning electron microscopy revealed the polypyrrole coating, while Raman and FTIR spectroscopies confirmed its molecular structure and completeness. The carbonyl iron/polypyrrole composites were produced as powders, and their electrical characteristics were described. Sulfuric acid (SA), p-toluenesulfonic acid (pTSA), and 2-naphthalenesulfonic acid (2NS) were the three dopants used to prepare the electrodeposition of polypyrrole on AA2024-T3 by applying a constant voltage. Using pTSA and 2NS dopants, polypyrrole was effectively electrodeposited onto AA2024-T3, demonstrating superior corrosion protection compared to bare AA2024-T3 (Lin et al., 2025).

Electrodeposition of PPy onto mild steel (MS) is a substantial work because the oxidation potential of MS is lower than that of the monomer (pyrrole). Since the potential required for the oxidation of monomer is high, it causes either dissolution or formation of passive layers on active metals. The actual reduction potential of pyrrole depends on the character of the dopant anion. The potential required for initiating pyrrole polymerization is high. At this potential, PPy deposition suffers from metal dissolution or the formation of low-conductivity oxides. The proper selection of electrolytes is required. The electrolyte should form a conductive passive film on the metal, allowing further deposition of PPy and enhancing adhesion. In this regard, sodium potassium tartrate (Na-K tartrate), an electrolyte, has been chosen, which passivates the MS and provides charge for the oxidation of pyrrole.

MATERIALS AND METHODS

Materials

Commercial-grade mild steel (MS) samples measuring 3 cm × 3 cm were purchased from the local market in Kathmandu. The MS was composed of carbon (0.17%), silicon (0.40%), manganese (0.8%), phosphorus (0.04%), sulfur (0.04%), and the remaining proportion of iron by weight. It was abraded with SiC paper of grades #100, #220, #320, #600, #800, and #1000. Dust particles adhered to the sample, and greasy materials were removed by rinsing with acetone. It was then abraded with #1200 and #1500 grade SiC paper, sonicated in ethanol for 10 minutes, and air-dried beforehand, before carrying out electropolymerization of pyrrole on the samples and performing electrochemical measurements.

Pyrrole (C_4H_4NH), sodium chloride (NaCl), sulphuric acid (H_2SO_4), and sodium-potassium tartrate were procured from Fischer Scientific, India. Sodium acetate (Merck, India) and acetone (Paskem Fine Chemical, India) were also procured. The sand was collected from the Melamchi Water Supply Project in Kirtipur. Solutions of the required concentrations were prepared as needed for the experiment.

Electrochemical Synthesis of PPy

The PPy coating on the abraded MS samples was performed using anodic polarization and cyclic voltammetry (CV) with a Hokuto Denko HA-151 potentiostat, which was operated by custom LabVIEW software running on an IBM computer. In a three-electrode configuration, the MS sample served as the working electrode (WE). In contrast, a saturated calomel electrode (SCE) was utilized as the reference electrode. A graphite rod was employed for the counter electrode (CE). The coating of polypyrrole on MS was performed by electrochemically in various concentrations of pyrrole and Na-K tartrate electrolyte by anodic polymerization. After a series of experiments varying the concentration of pyrrole and Na-K tartrate, 0.4 M pyrrole and 0.1 M Na-K tartrate were selected as the most suitable concentration composition based on anodic polarization and cyclic voltammetry (CV) measurements. The PPy was deposited on MS using an optimized composition of 0.4 M pyrrole containing 0.1 M Na-K tartrate solution by potentiodynamic polarization (PDP). The PPy coating was first achieved through anodic polarization by changing the voltage from -0.6 V to +2.5 V at a scan rate of 1 mV/s. The CV was then performed to electrochemically polymerize pyrrole onto the MS surface at a scan rate of 20 mV/s. The PPy-coated MS was washed with Milli-Q water after polymerization, subjected to air drying, and stored in a desiccator for the corrosion test.

Characterization of Polypyrrole Coating

The elemental composition of polypyrrole (PPy) was established using an energy-dispersive X-ray (EDX) microscope equipped with a JEM-1200EX (JEOL, Tokyo, Japan). The surface structure of the PPy coating was assessed by means of a scanning electron microscope (SEM).

Corrosion Test in Buried Medium

The corrosion protection of MS coated with PPy was examined in an artificial corrosive medium. The corrosive condition was created by filling a plastic bottle of equal size with sand of varying concentrations of corrosive substances, such as sodium chloride (NaCl) and sulfuric acid (H_2SO_4). The MS and MS coated with PPy were buried in sand. The experimental setup is illustrated in Figure 1 below. Prior to each polarization measurement, the grazed MS coupons were placed in the test solution for 30 minutes to achieve a constant open-circuit potential (OCP).

Potentiodynamic polarization was used to examine the PPy coating's corrosion prevention performance by sweeping the potential ±300 mV from the open-circuit potential (OCP) with a 1 mV/s scan rate. The corrosion potential and corrosion current density were acquired by extrapolating the linear Tafel segments of the anodic and cathodic curves. Applying the relation (1), the inhibition efficiency (IE) was calculated from the corrosion current (i_{corr}) value.

$$\text{Inhibition efficiency } (IE) \text{ in } \% = \frac{icorr - i'corr}{icorr} \; x \; 100 \qquad (1)$$

Where i_{corr} represents the corrosion current density of MS, and i'_{corr} represents the corrosion current density of PPy-coated MS.

Figure 1. MS and MS coated with PPy buried in the sand

RESULTS AND DISCUSSIONS

Polymerization of Pyrrole onto the Mild Steel Surface

Passivation of the MS surface with an active electrical composition is essential for the polymerization of pyrrole; therefore, selecting the electrolytes is an indispensable and inevitable process. Pyrrole undergoes oxidation at a high potential, which makes it challenging to polymerize onto mild steel (MS) surfaces. Therefore, the active dissolution of the mild steel surface was observed using acids as electrolytes (Hamtak et al., 2023). There was no passivation and polymerization of pyrrole using sulphuric acid, nitric acid, phosphoric acid, hydrochloric acid, acetic acid, sodium phosphate, and potassium chloride. Therefore, the electroactive passivation of MS is essential for polymerization. As a result, an electrolyte, sodium potassium tartrate (Na-K tartrate), with polarization behavior similar to oxalic acid, was chosen for polymerization.

Polymerization of Pyrrole by Cyclic Voltammetry

Figure 2 shows the cyclic voltammetry (CV) of polypyrrole (PPy) coating on MS in 0.4 M pyrrole in 0.1 M Na-K Tartrate. The CV was performed to electrochemically polymerize pyrrole onto the MS surface at a scan rate of 20 mV/s. A concentration of 0.4 M pyrrole in 0.1 M Na-K tartrate was used for the deposition of polypyrrole. A potential window ranging from -0.6V to 2.0V was used in this study.

In the initial cycle, an oxidation peak appeared at -0.43 V and then vanished in successive cycles. This oxidation peak is associated with the iron oxidation. However, this peak was diminished in subsequent cycles. Due to the oxidation of pyrrole, the current began to rise quickly at +0.902 V potential during the CV for optimum concentration. Due to the self-catalytic behavior resulting from the development of PPy, the current changes negatively during positive cycles (X. Jiang et al., 2020). In the second cycle, a slight increase in current was observed. It was determined that the monomer oxidation process was responsible for this current rise. Meanwhile, the number of cycles also led to an increase in the corresponding oxidation current values. Thus, the CV results established that the PPy layer formed gradually and covered the MS surface as the number of cycles increased. Furthermore, as the number of scans increased, the thickening of the homogeneous and uniform PPy coatings increased. The outcome shows that the thickness and stability of PPy grew with the number of cycles.

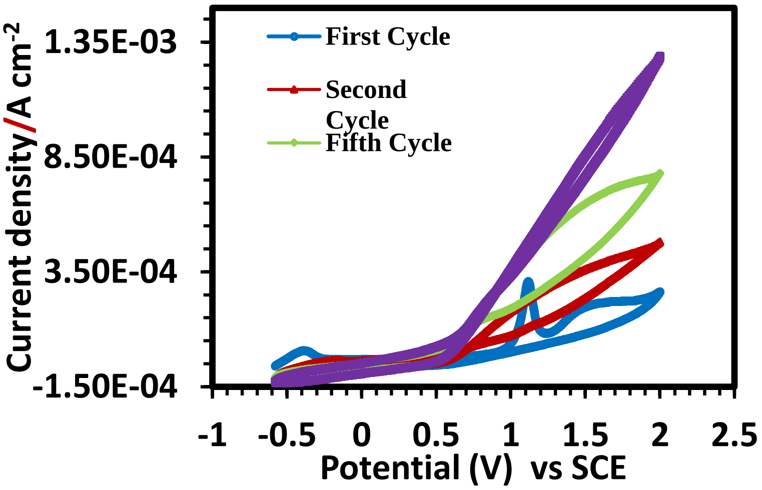
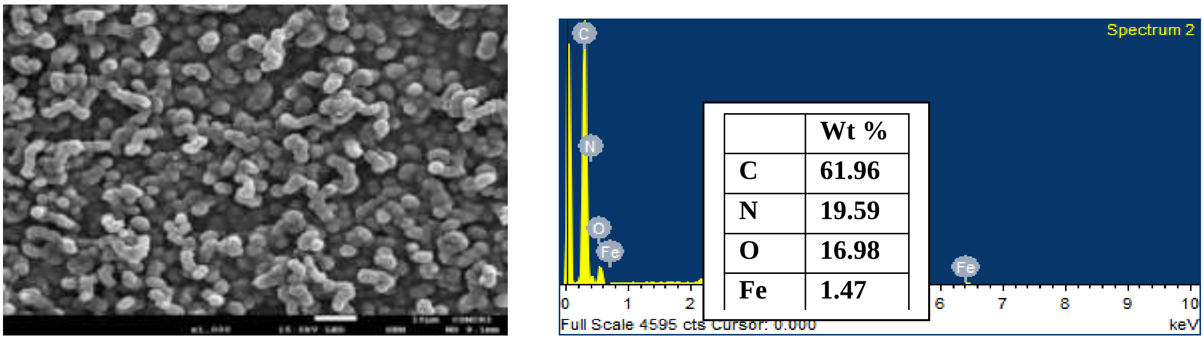


Figure 2. PPy coatings on MS acquired by cyclic voltammetry in 0.4 M pyrrole + 0.1 M Na-K Tartrate

Surface Analysis

The scanning electron microscopy (SEM) image of the PPy-coated MS surface is shown in Figure 3. The energy-dispersive X-ray (EDX) spectrum is also shown in Figure 3. The PPy layer was composed of thick, compact, cauliflower-like coverings (Mirzaee et al., 2024). The elements carbon, nitrogen, oxygen, and iron are readily apparent in the EDX spectra, confirming the development of the PPy coating.

It is tough to remove the PPy coatings from the MS surface. This also confirms its adherence to the MS.



	Wt %
C	61.96
N	19.59
O	16.98
Fe	1.47

Figure 3. SEM image of Ppy-coated MS with its corresponding EDX elemental analysis

Corrosion Study

Variation of Open Circuit Potential (OCP) with Exposure Time

To study the effectiveness of the PPy layer in preventing corrosion, open-circuit potential (OCP) was recorded for 2 minutes in a sand sample comprising 0.1 M NaCl and 0.1 M H_2SO_4, separately, for 30 minutes to achieve a constant open-circuit potential. Figure 4 describes the OCP of MS and PPy-coated MS in 0.1 M NaCl and 0.1 M H_2SO_4 with time. The OCP of PPy-coated MS remained constant in both media after 12 minutes, indicating the development of a stable film. The uncoated mild steel (MS) OCP was shifted to a more negative potential in 0.1 M H_2SO_4 than in 0.1 M NaCl.

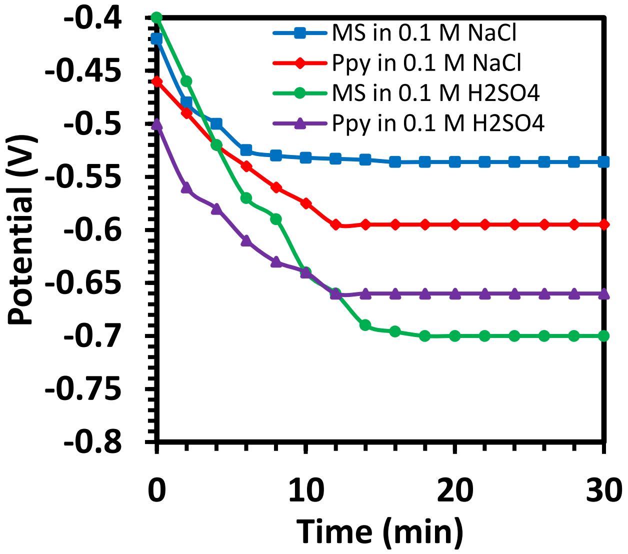


Figure 4. OCP measurement of the MS coupons without and with Ppy coatings for 30 minutes

PPy-coated MS buried in a sand sample containing 0.1 M NaCl solution showed -0.595 V OCP, which is relatively constant after 12 minutes of measurement, and PPy-coated MS shifted to more negative than bare MS. Similarly, PPy-coated MS showed -0.66 V OCP in a sand sample containing 0.1 M H_2SO_4 solution, which was slightly positive than bare MS and remained constant after 10 minutes. The modest alteration in OCP indicates that the protective thin layer on the MS surface is sturdy. This layer acts as a physical barrier to reduce MS corrosion. The change in OCP of PPy-coated MS in both cases is less than 85 mV compared to MS. This consequently indicates that the PPy coating acts as a mixed corrosion inhibitor.

Potentiodynamic Polymerization

The corrosion features of PPy-coated MS in buried sand containing 0.1 M NaCl and 0.1 M H_2SO_4 have been investigated. Figure 5 shows potentiodynamic polarization curves. The electrochemical parameters obtained and presented in Table 1 include corrosion current density ($i_{\_corr}$), corrosion potential ($E_{\_corr}$), anodic and cathodic slopes, and inhibition efficiency (IE).

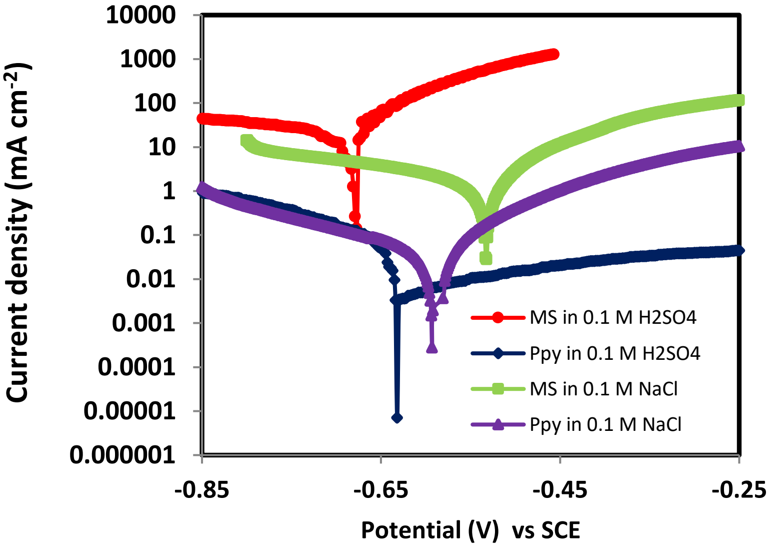


Figure 5. Potentiodynamic polarization curves showing corrosion protection behavior in 0.1 M H_2SO_4 and 0.1 M NaCl

Compared to the PPy-coated surfaces, the current density on the bare MS surface was significantly higher. In general, improved corrosion protection is reflected by a lowering of i_{corr} (signifying a reduction in the corrosion current).

The PPy-coated MS showed a reduction of current density. Upon comparison with uncoated MS, the OCP of PPy-coated MS shifted in a positive direction in 0.1 M H_2SO_4, indicating the development of a protective film for the aggressive medium (Shabani-Nooshabadi et al., 2018; Shabani-Nooshabadi & Karimian-Taheri, 2015). Likewise, the corrosion potential (Ecorr) of PPy-coated MS swung in a negative direction in 0.1 NaCl. However, the difference between the uncoated MS and PPy-coated OCP values is minimal (< 85 mV), indicating that the PPy coating functions as a mixed-type inhibitor (Gvozdenovi et al., 2012; Jafari et al., 2016). The cathodic and anodic current density was suppressed significantly in both cases. The effectiveness of the corrosion inhibition was approximately 99%. In an acidic solution, the PPy coating exhibits exceptional resilience to corrosion.

In a 0.1 M NaCl solution, the cathodic constant (β_c) exhibits values of 10^1 mV/decade, corresponding to oxygen reduction.

This indicates that PPy coating is an effective barrier that protects the MS surface (Mirzaee et al., 2024). These coatings on MS typically show the anodic slope (βa) and cathodic slope (βc) in both acidic and aqueous saline environments (Pawar et al., 2006; Shabani-Nooshabadi et al., 2018).

Table 1. Electrochemical polarization parameters for Ppy-coated MS in different media

Media	**Sample**	**β_a (V/decade)**	**β_c (V/decade)**	**I_{corr} (mA/cm2)**	**E_{corr} (V)**	**Corrosion Rate (mm/year)**	**Inhibition Efficiency (%)**
0.1M H2SO4	MS	0.091	-0.200	17.54	-0.694	203.77	
	Ppy Coated MS	0.055	-0.199	0.0154	-0.622	0.178	**99.91**
0.1M NaCl	MS	0.054	-0.127	1.351	-0.530	15.69	
	Ppy Coated MS	0.069	-0.101	0.024	-0.593	0.278	**98.22**

According to reports, the inhibitory activity of the C–N group adsorbed on the MS surface provides corrosion protection through the PPy coating. Both oxidation and reduction reactions are suppressed by PPy's ability to adsorb onto the metal surface (Jafari et al., 2016). Additionally, studies indicate that using PPy as a corrosion protective layer decreases corrosion currents in acidic and aqueous saline conditions (Kumar, 2023; Ananda Kumar et al., 2008; Mahato & Cho, 2016; Pawar et al., 2006). Iron dissolves during the anodic process, while oxygen is reduced on the PPy coating in the specified medium during the cathodic reaction (Rajyalakshmi et al., 2020).

To explain the above results, the following has to be considered for MS in the above medium: the following reactions happen (Rajyalakshmi et al., 2020):

$$\text{Oxidation (anodic reaction):}\quad Fe \rightarrow Fe^{2+} + 2e$$

$$\text{Reduction (cathodic reaction):}\quad H_2O + \tfrac{1}{2} O_2 + 2e \rightarrow 2OH$$

CONCLUSIONS

Polypyrrole (PPy) was synthesized from the monomer pyrrole using electrochemical oxidative methods on MS. The main goal of this study was to identify an electrolyte that promotes an adherent PPy coating on MS, capable of providing excellent corrosion protection in buried sand. Since electrolytes are crucial for the polymerization of pyrrole onto MS, Sodium potassium tartrate (Na-K tartrate) was selected as the novel electrolyte because it enhanced pyrrole passivation and polymerization on MS. Consequently, PPy was deposited on MS via electrochemical cyclic voltammetry (CV) from 0.1 M pyrrole containing 0.4 M tartrate to prevent corrosion. The CV showed an increase in current with the growth of the PPy film over successive cycles, and the anodic peak disappeared after the first cycle. No anodic dissolution was observed during the cathodic scan. This indicated an excellent alternative for polymerizing pyrrole onto MS surfaces with improved cyclic stability. SEM-EDX confirmed the formation of a thick, compact, cauliflower-like PPy film on MS, which was highly adherent to MS. The PPy film exhibited significant corrosion inhibition properties for mild steel in a buried sand mixture containing 0.1 M NaCl and 0.1 M H2SO4. The open circuit potential (OCP) of PPy-coated MS in both media revealed that PPy acted as a mixed-type inhibitor, due to the stable film and consistent potential over time. The anodic and cathodic current densities of PPy-coated MS were significantly reduced in both cases, resulting in inhibition efficiencies of 98.28% and 99.91% in buried sand containing 0.1 M NaCl and 0.1 M H_2SO_4, respectively. PPy coating on MS effectively provides corrosion protection in buried sand containing NaCl and H_2SO_4. This work assisted in achieving the ideal conditions for effective PPy coating on MS in Na-K tartrate solutions. Therefore, the outcome demonstrates that the PPy coating obtained in Na-K tartrate exhibits outstanding corrosion protection in buried sand.

For the polymerization of pyrrole onto MS, the study's findings emphasize the significance of the electrolyte. It also highlights the importance of PPy's adhesion and shape in preventing corrosion in buried sand. This study provides insight into the sustainable development of PPy coating on MS.

In the future, both potentiostatically and galvanostatically, PANI can be produced, forming a fine and consistent PANI layer, which can be further investigated for corrosion prevention. For the material's sustainability, corrosion prevention of PPy in soil and concrete environments can also be investigated. The roughness, morphological shape, and size of the PPy coating can also be investigated by atomic force microscopy (AFM) and transmission electron microscopy (TEM), as these factors impact adherence to the MS surface and, consequently, its corrosion behavior. The kinetics and the interface mechanism can also be studied. X-ray Photoelectron Spectroscopy (XPS) can also be used to analyze the elemental composition, chemical state, and electronic state of the element. This provides the information about the elements present, their chemical bonding environment, and their concentration at the surface.

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