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INVESTIGATING THE IMPACT OF VARYING QUANTITIES OF TiO_2 NANOPARTICLES ON THE ANTI-CORROSIVE CHARACTERISTICS OF TiO_2-EPOXY NANOCOMPOSITE COATINGS[†]

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Prepared were pills coated with TiO_2-epoxy nanocomposites, and their anti-corrosive properties were studied by examining the impact of varying amounts of TiO_2 nanoparticles in the epoxy resin. The anti-corrosive characteristics of pills were investigated employing electrochemical impedance spectroscopy (EIS). Based on the EIS results, the sample containing 0.01 mg of TiO_2 demonstrated the highest impedance value, indicating superior corrosion resistance and better anti-corrosion properties than the other samples. Also, this sample has the lowest corrosion current density among the all samples, with a value of 1.329E-07 mA/cm^2, which shows that this sample has the best corrosion resistance and a slower rate of corrosion compared to the other samples.
Keywords: *Epoxy; TiO_2 nanoparticles; Nanocomposite; Electrochemical Impedance Spectroscopy (EIS); Coatings; Sol-gel synthesis*
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1. INTRODUCTION

Corrosion is a natural process that can occur when metallic materials are exposed to the environment. It is the gradual degradation or deterioration of the material and its properties, typically a metal, due to electrochemical reactions occurring at the surface. Corrosion can induce material damage and eventual destruction, leading to economic burden and endangering human well-being and safety [1]. To prevent corrosion of metal materials, it is essential to apply a protective coating. This practice is commonly employed globally to address a wide range of corrosion issues and mitigate their associated consequences. Despite efforts to combat it, corrosion remains a major challenge for Steel-framed structures, as it can lead to material property degradation, reduced Support capacity, compromised safety, and shortened Performance life of structures [2]. Corrosion has attracted much research interest, and various methods have been developed to provide proper protection. However, the cost of corrosion and its consequences can be substantial. Hence, it is imperative to persist in the exploration and advancement of fresh approaches to combat corrosion and minimize its societal consequences. Accordingly, discovering a corrosion prevention technique that is highly effective, sustainable, durable, environmentally friendly, and economical is of utmost importance. The polymeric coating is a popular option for corrosion prevention because of its ease of production and ability to create a barrier on the material surface. Epoxy resin is commonly used as an anticorrosion coating due to its excellent adhesion, chemical resistance, and mechanical properties. Epoxy coatings are particularly effective in protecting metal surfaces from corrosion caused by exposure to harsh environments, such as saltwater, acidic solutions, and extreme temperatures. When applied as a coating, epoxy resin forms a hard, durable film that separates the metal surface from its surrounding conditions. This protective coating impedes moisture, oxygen, and other corrosive agents from reaching the metal surface, which helps to prevent corrosion [3,4].

In recent decades, researchers have conducted numerous studies to enhance the barrier properties of polymeric coatings [5-10]. One approach is to incorporate nanoscale particles into the polymer coatings, aiming to improve the coatings' anticorrosion and protective characteristics through various pathways. Pore filling, matrix defect reduction, and crack bowing, deflection and bridging are some of the methods identified [11]. Additionally, nano-additives can serve as connecting bridges between matrix molecules, decreasing the total unoccupied volume and promoting bonding [12-14]. These mechanisms delay the infiltration activity, slowing the spread of corrosive substances within the coating and reducing the corrosion rate on the material surface. To significantly improve the properties of epoxy, a larger interfacial area within the epoxy and fillers is required, which is influenced by factors such as particle size, the uniformity of nanoparticle distribution, and the volume proportion of nanoparticles in the epoxy matrix. TiO_2 nanoparticles are widely used as useful nano-sized filler due to their photocatalytic effect [15].

This phenomenon causes the TiO_2 nanoparticles to emit a large quantity of electrons when exposed to UV radiation. The electrons that are emitted trigger a photochemical reaction that acts on the Corrosive substances present on the surface of the coating, leading to additional corrosion inhibition. Although ultraviolet light can release radicals that may break down the polymer coating layer's molecular structure, this mechanism also provides the nanoparticles with an antimicrobial property that can eliminate bacteria found on the surface, potentially causing corrosion [16,17]. Because of their photocatalytic effect, Titanium dioxide nanoparticles are widely used for their ability to inhibit odors, self-clean, and resist fouling.

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The objective of this research was to examine how the anti-corrosion properties of pills coated with a TiO_2-epoxy nanocomposite were impacted by different quantities of TiO_2 nanoparticles. The anti-corrosion properties of the samples were assessed by performing EIS after exposing the coated pills to a 1 M HCL solution. In addition, TiO_2 nanoparticles were examined utilizing XRD, AFM, SEM, UV-Vis spectrophotometry, and FTIR to gain insight into their properties. By investigating the relationship between the amount of TiO_2 and the Corrosion resistance of coatings, this study contributes to the development of more effective coatings for various applications. The findings may also have implications for the design of more efficient corrosion-resistant materials.

2. EXPERIMENTAL PROCEDURE

2.1. Synthesis of Titanium dioxide nanoparticles

TiO_2 nanoparticles were prepared via the sol-gel technique using Titanium tetra iso propoxide, ethanol (C_2H_6O), nitric acid (HNO_3), and distilled water. First, the initial solution was prepared by dissolving a certain amount (2.5 ml) of TTIP in 45 ml of solvent, including distilled water (37.5 ml) and ethanol (7.5 ml). This solution was stirred for 1h. Then, drops of 1 ml of HNO_3 were added to the solution until it became transparent and clear. The obtained solution was refluxed at 70°C for 2h. After forming the gel, it was further slowly dried at 60°C for 3h. Finally, the prepared nano-powders were annealed at 400°C for 3h in the furnace in an air atmosphere.

2.2. Preparation of TiO_2-epoxy nanocomposites

To prepare TiO_2-epoxy nanocomposites, the specified amount of TiO_2 nanoparticles (0.002, 0.004, 0.006 and 0.01 mg) was transferred into separate clean and dry beakers. An equal amount of epoxy (obtained from Ahlia Chemicals Company) was added to each beaker, ensuring that the ratios were consistent across all mixtures. The contents of each beaker were mixed thoroughly using a clean stirrer until a homogeneous mixture was obtained. Once the mixtures were ready, they were sonicated using an ultrasonic bath for 2h to improve their dispersion. After that, the hardener was added to the beaker and mixed for one minute.

2.3. Coating pills with TiO_2-epoxy nanocomposites

Four iron pills measuring 1.5 cm in diameter and 3 mm in thickness were used as the substrate for coating. Prior to coating, the iron pills were cleansed and degreased with acetone and subsequently dried completely. Using the spin coating method, each iron pill was coated with the different TiO_2-epoxy mixtures one at a time, starting with the mixture containing 0.002 mg of TiO_2, followed by 0.004 mg, and so on. After each coating, the pill was spun at a constant speed of 2000 rpm for a set time to ensure uniform coverage of the TiO_2-epoxy nanocomposite. After all plates were coated and rotated, they were left at room temperature for at least 5 days to cure.

2.4. Characterization

The XRD spectra of titanium dioxide nanoparticles were recorded utilizing a D8 Advance Bruker system with Ni filtering and Copper K-alpha radiation with a wavelength of 0.15406 nm, covering a 2θ range of 20°-80°. A Nanosurf AG Naio AFM was utilized to capture the AFM image of the TiO_2 nanoparticles. The SEM Vega 3LM was used to analyze the morphology of both the nanoparticles and nanocomposites. The FTIR spectrums were recorded with Shimadzu 8300 over a range of wave numbers from 400 to 4000 cm^{-1}. Optical analysis was conducted using the Unico 4802 dual beam spectrophotometer. To assess the anti-corrosion characteristics of the coated pills, the samples were submerged in a 1 M HCl solution, which served as an electrolyte and provided a conductive medium for the electrochemical reactions that occurred during corrosion. Then, The EIS analysis was performed using Ivium Technology to investigate the anti-corrosion properties of pills coated by TiO_2-epoxy nanocomposites containing different amounts of TiO_2 nanoparticles.

3. RESULTS AND DISCUSSION

3.1. XRD Analysis

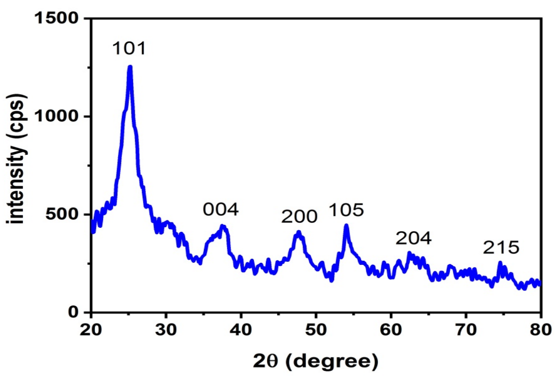

Figure 1. XRD spectrum of prepared TiO_2 nanoparticles.

The XRD pattern of the fabricated TiO_2 nanoparticles is depicted in Figure 1. The crystal planes of (101), (004), (200), (105), (204), and (215) are represented by diffraction peaks at 2θ values of 25.23°, 37.76°, 47.87°, 53.89°, 62.55°, and 74.87°, as observed in the XRD spectrum. The XRD pattern matches the standard reference XRD pattern of TiO_2 (JCPDS Card No.21-1272), thus verifying the successful synthesis of anatase-phase TiO_2 nanoparticles via the sol-gel method. The most intense peak, located at 2θ value of 25.23°, indicates the preferred crystal plane of (101) for anatase phase of titanium oxide.

3.2. AFM image

Performing atomic force microscope (AFM) analysis on TiO_2 nanoparticles offers valuable insights into the surface morphology and properties of the nanoparticles. AFM image of TiO_2 nanoparticles is shown in Figure 2. The surface of the fabricated titanium dioxide nanoparticles exhibits a rough and irregular texture, as evidenced by the root mean square (RMS) height of 122.4 nm. Furthermore, the mean particle size was measured to be 76.84 nm. These results provide valuable insights into the properties and potential applications of titanium dioxide nanoparticles in various fields, including nanotechnology, materials science, and biomedicine.

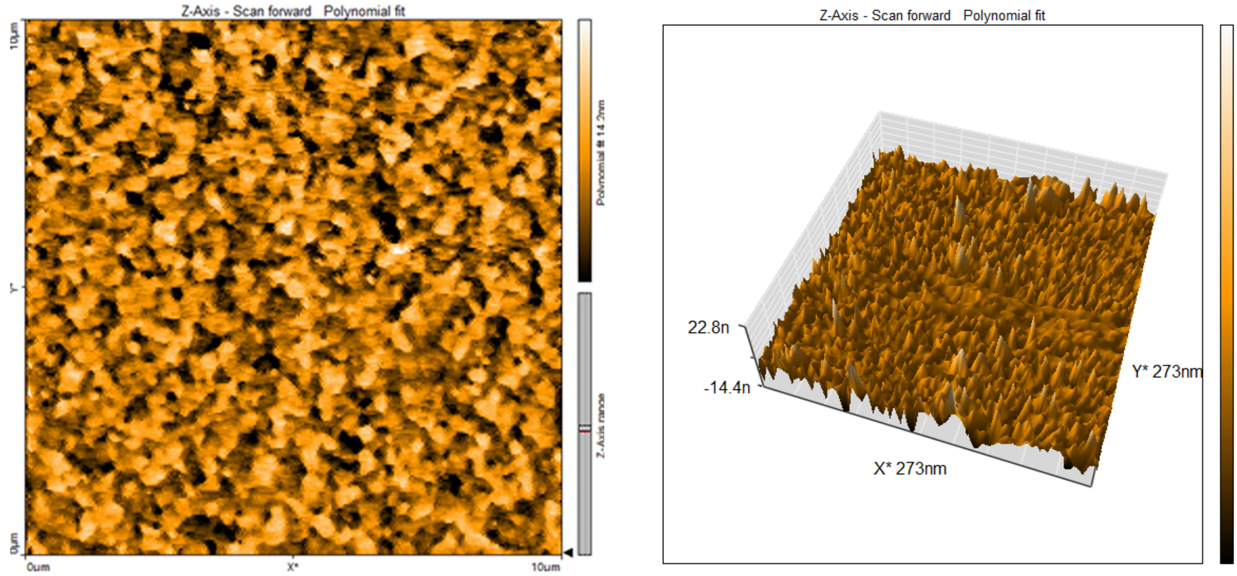

Figure 2. AFM image of synthesized TiO_2 nanoparticles

3.3. SEM Images

Examining the surface morphology of materials, such as titanium dioxide nanoparticles and TiO_2-epoxy nanocomposites, can be effectively achieved through the use of SEM. The SEM image of prepared TiO_2 nanoparticles and TiO_2 (0.002 mg)-epoxy nanocomposite are shown in figure 3. Upon analyzing SEM images of TiO_2 nanoparticles (Fig. 3a), it is evident that the surface is rough and irregular, with lumps of varying shapes and sizes present throughout. The existence of irregular lumps at the nanoparticle surface is particularly noteworthy, as it suggests that the surface is not homogeneous. This roughness and lack of uniformity is consistent with the results of atomic force microscopy, which also showed a non-uniform and rough surface for these nanoparticles. According to Figure 3b, the SEM image of the TiO_2 (0.002 mg)-epoxy nanocomposite revealed a polished and almost uniform surface (Fig. 3b). The SEM image showed that the nanoparticles were distributed throughout the epoxy matrix, visible as small dots or clusters. Furthermore, the distribution of the nanoparticles appeared to be uniform throughout the sample.

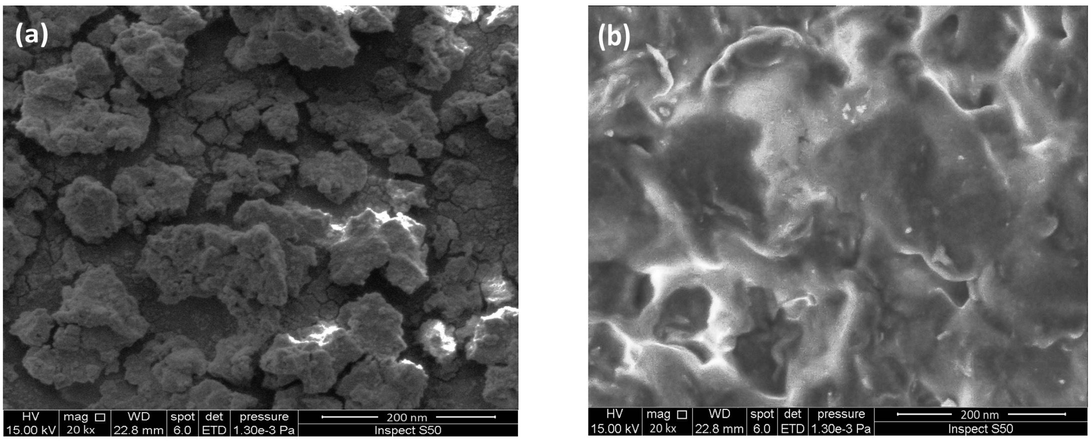

Figure 3. SEM micrographs of (a) TiO_2 nanoparticles and (b) TiO_2 (0.002 mg)-epoxy nanocomposite

3.4. UV-Vis spectroscopy

Titanium dioxide nanoparticles exhibit unique optical properties. In this study, the optical absorption properties of TiO_2 nanoparticles were investigated by measuring their absorption spectrum using UV-Vis analysis. As illustrated in Figure 4, the absorption curve showed a sharp absorption edge at a wavelength of 350 nm, which is a significant factor for understanding the optical response of TiO_2 nanoparticles. The absorption edge is the wavelength at which the material starts to absorb light due to valence-to-conduction band electronic transitions.

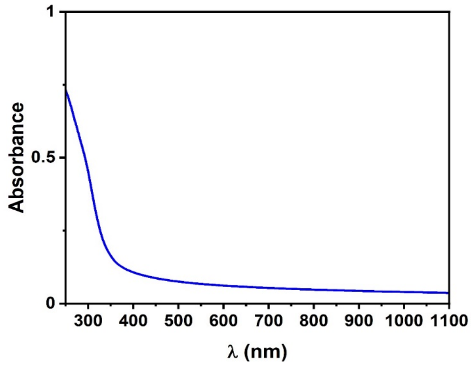

Figure 4. Optical absorption of synthesized TiO_2 nanoparticles

3.5. FTIR

Figures 5 and 6 depict the FTIR spectra of TiO_2 nanoparticles and an epoxy-TiO_2 (0.002 mg) nanocomposite, respectively. The FTIR spectrum for the anatase phase of TiO_2 nanoparticles displayed a broad vibration peak between 500 and 800 cm^{-1}, which was attributed to vibrational mode associated with Ti-O bonds. The incorporation of TiO_2 nanoparticles into the epoxy resin resulted in overlapping spectral features between 500 and 800 cm^{-1}, due to the presence of a minor concentration of TiO_2 nanoparticles in the epoxy resin matrix. The absorption band centered at 915 cm^{-1} in the epoxy-TiO_2 nanocomposite is indicating the bending motion of the C-O bond in the epoxy structure.

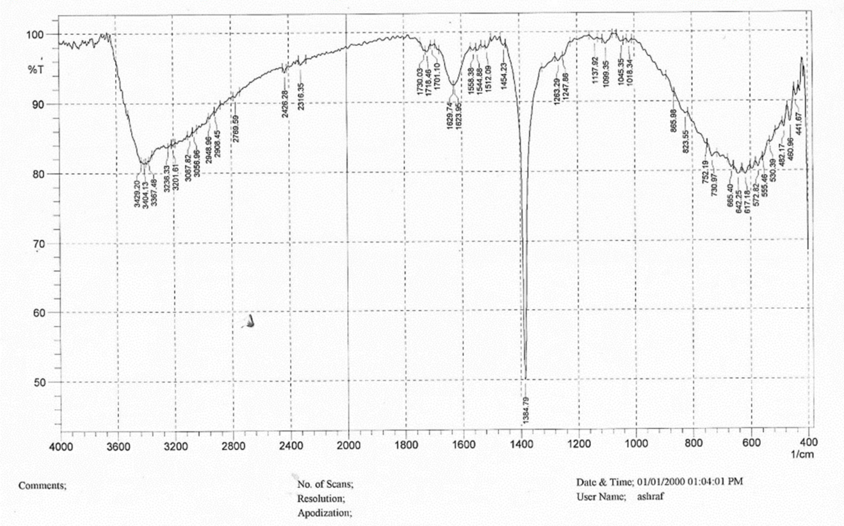

Figure 5. FTIR spectra TiO_2 nanoparticles

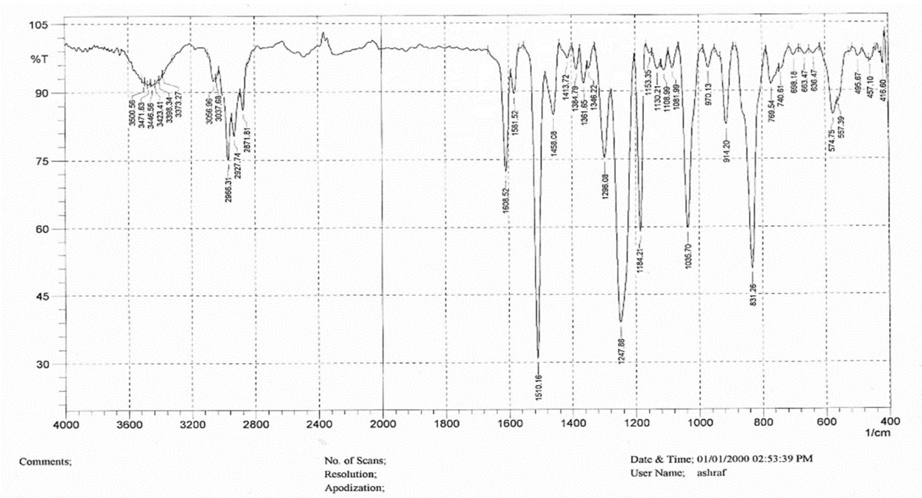

Figure 6. FTIR spectra of epoxy-TiO_2 (0.002 mg) nanocomposite

3.6. EIS

EIS is a potent method employed to analyze and evaluate the ability of various coatings to resist corrosion. Corrosion is a natural process that occurs when metals react with their environment, and it can lead to serious damage and deterioration of structures. EIS can be used to evaluate the effectiveness of coatings in preventing corrosion by measuring the electrical response of a coated metal sample to an alternating current (AC) signal. The process of conducting an EIS analysis involves applying an AC signal with a range of frequencies to a coated metal sample submerged in an electrolytic solution. The resulting electrical response is then measured and plotted on a graph called a Nyquist plot. The Nyquist diagram is a graphical representation in the complex plane that shows the relationship between the real and imaginary components of impedance. The curve obtained from the Nyquist plot is then analyzed to determine the coating's anti-corrosion performance. The Nyquist plot obtained from an EIS analysis typically shows a semicircle that corresponds to the impedance at the electrode/electrolyte interface. The semicircle observed in the Nyquist plot corresponds to the charge transfer resistance, which represents the level of resistance that the coating offers to electron transfer at the interface between the metal and electrolyte. By analyzing the shape and size of the semicircle, the coating's anti-corrosion properties can be determined.

To analyze the graphs obtained from EIS analysis, an electrical equivalent circuit (EEC) diagram is often used. The simplified electrical circuit diagram, also known as the equivalent circuit diagram, represents the physical mechanisms occurring at the interface between the metal and electrolyte. The parameters of the circuit can be established by matching the experimental quantities to the ECC diagram, which can then be employed to assess the anti-corrosive characteristics of the coating. The EIS test results for different samples of TiO_2-epoxy nanocomposite coated pills with varying amounts of TiO_2 immersed to 1 M HCL for different time intervals were obtained by fitting an appropriate electrical equivalent circuit (R1(R2C1)(R3C2)), consisting of three elements: R1 (The resistance of the solution), R2C1 (The resistance to charge transfer at the external surface of the coating and its capacitance), and R3C2 (The resistance to charge transfer at the internal surface of the coating and its capacitance), as shown in Figure 7.

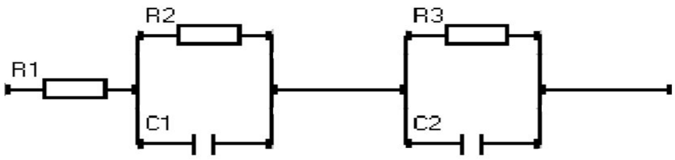

Figure 7. Equivalent electrical circuit (EEC)

Following this, the information was examined and condensed into Table 1. The values of R1, R2, R3, C1, and C2 change with time and TiO_2 concentration, indicating the progression of the corrosion process and the influence of the TiO_2-epoxy nanocomposite coating on the pills' susceptibility to corrosion, As indicated by Table 1.

Table 1. The EIS parameters of TiO_2-epoxy nanocomposite coated pills after 15-, 30- and 90-minutes immersion time

Sample	Immersion time (min)	R1 (Ω)	R2 (Ω)	R3 (Ω)	C1 (f)	C2 (f)
	15	4.66E-01	1.18E+01	1.63E+00	1.57E-04	1.10E-04
0.002 mg TiO_2	30	4.45E-01	1.10E+01	1.55E+00	1.47E-04	1.11E-04
	90	4.55E-01	1.15E+01	1.58E+00	1.50E-04	1.11E-04
	15	3.74E-01	7.98E+00	2.43E+00	1.56E-04	8.51E-05
0.004 mg TiO_2	30	3.72E-01	9.08E+00	2.51E+00	1.44E-04	8.46E-05
	90	3.72E-01	1.01E+01	2.48E+00	1.30E-04	8.58E-05
	15	3.93E-01	2.75E+01	4.63E+00	1.30E-04	8.99E-05
0.006 mg TiO_2	30	3.96E-01	2.86E+01	5.82E+00	1.37E-04	8.78E-05
	90	3.97E-01	2.98E+01	5.94E+00	1.33E-04	8.73E-05
	15	5.41E-01	6.91E+01	7.53E+00	2.99E-04	1.29E-04
0.01 mg TiO_2	30	5.69E-01	9.06E+01	8.74E+00	2.62E-04	1.17E-04
	90	5.77E-01	1.02E+02	9.77E+00	2.64E-04	1.15E-04

The Nyquist diagram of all samples, as shown in Figure 8, exhibits a semi-circular shape. It is important to note that the diameter of the Nyquist diagram is directly related to the anti-corrosion properties of the sample, with larger diameters indicating better anti-corrosion properties. By increasing the amount of titanium dioxide from 0.002 mg to 0.01 mg, the impedance values increased. The pills with higher TiO_2 concentrations showed a slower rate of corrosion. Furthermore, the sample with 0.01 mg of titanium dioxide demonstrated the highest impedance value, indicating superior corrosion resistance and more effective corrosion protection compared to the others. The amount of titanium dioxide present in the sample has a notable impact on its impedance and corrosion inhibition capabilities. Increasing the amount of titanium dioxide results in higher impedance values, indicating better anti-corrosion properties. Incorporating TiO_2 into the epoxy nanocomposite enhances the pills' ability to resist corrosion by producing a dense and protective coating on the pills' surface, which impedes the penetration of acid and decelerates the corrosion process. TiO_2 is known for its excellent chemical stability, high surface area, and photocatalytic properties. When added to the epoxy nanocomposite, TiO_2 particles act as physical barriers that limit the access of the acid to the pill's surface, which reduces the rate of corrosion and the amount of material that is corroded. In addition, the TiO_2 particles improve the adherence of the coating to the pill's exterior, thereby inhibiting the coating from peeling off and exposing the underlying metal to the corrosive environment. The presence of TiO_2 particles improves the mechanical characteristics of the coating, providing it with greater durability and strength against wear and abrasion. Furthermore, TiO_2 is known to have photocatalytic properties, which can lead to the development of a self-cleaning coating on the pills' surface. When exposed to UV light, TiO_2 particles generate reactive oxygen species that can break down organic contaminants and bacteria on the pills' surface, leading to an enhancement in the coating's anti-corrosion performance.

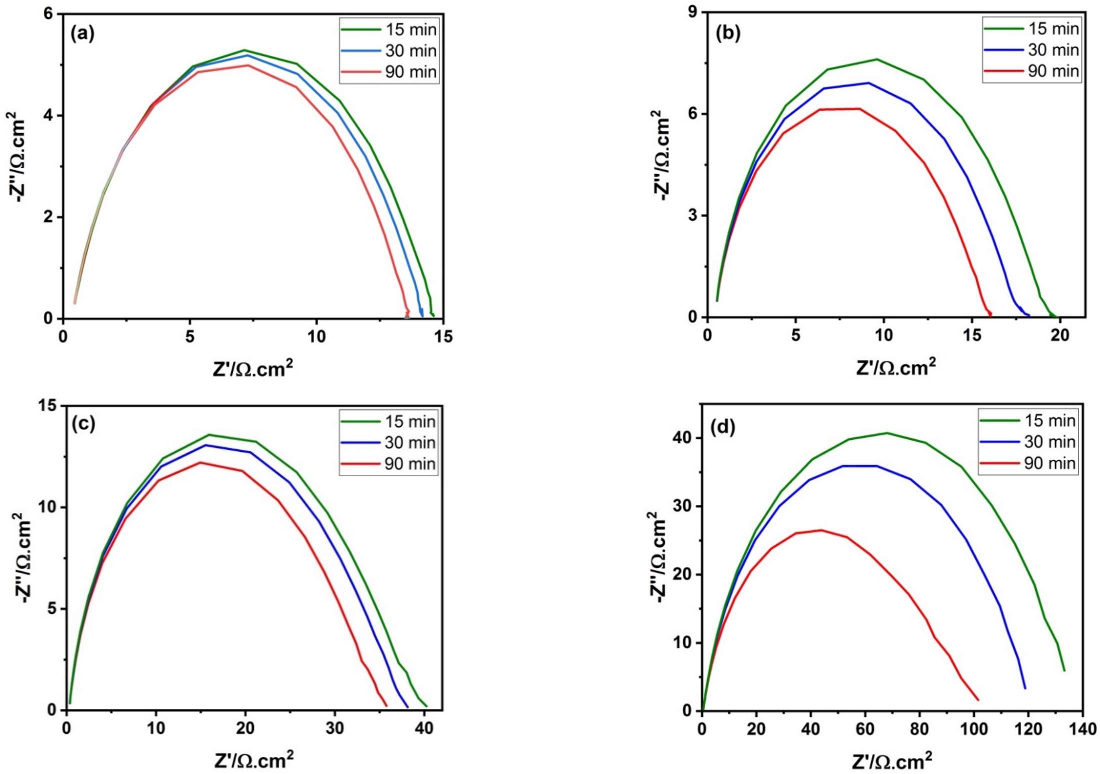

Figure 8. Nyquist plots of the TiO_2-epoxy coated pills immersed in 1 M HCL with varying quantities of TiO_2: (a) 0.002 mg, (b) 0.004 mg, (c) 0.006 mg and (d) 0.01 mg, after 15-, 30- and 90-minutes immersion time

Additionally, the effect of immersion time on impedance and anti-corrosion properties was also investigated. As seen in Figure 8, with an increase in the time of exposure to the solution, the impedance of all samples decreased, leading to a decrease in the diameter of the Nyquist diagram and, as a result decrease in anti-corrosion properties. The impact of immersion time on the anti-corrosive performance of coatings is an essential aspect of evaluating the durability and effectiveness of materials in real-world applications. Corrosion is a natural process that occurs when metals react with their environment, and it can cause significant damage and deterioration to structures and materials. Therefore, the ability of coatings to prevent or resist corrosion over time is crucial in ensuring their long-term performance. As materials are exposed to corrosive environments for extended periods, the effectiveness of coatings in preventing corrosion may decrease. This decrease in effectiveness can be attributed to a variety of factors, such as the breakdown of the coating or the depletion of its anti-corrosive agents. As a result, the anti-corrosive properties of the samples may weaken, leading to an increase in the rate of corrosion over time. Studying the influence of immersion time on the ability of coatings to inhibit corrosion can provide valuable insights into their long-term durability and effectiveness. By exposing coated materials to corrosive environments for varying durations, researchers can evaluate the speed of corrosion and the effectiveness of the protective film in preventing it. This information can then be used to improve the design and formulation of coatings, ensuring that they remain effective in preventing corrosion over extended periods.

Tafel analysis was performed for all samples to assess the corrosion performance of the coatings. Assessing the corrosion performance of metallic materials and coatings using this technique is a widely employed method. This analysis is based on measuring the current density of the sample in a corrosive environment (j_{corr}) as a function of the applied potential. To conduct a Tafel analysis, the sample is submerged in an electrolyte solution, and a slight potential difference is introduced between the sample and a reference electrode. The current passing through the sample is computed and used to calculate the corrosion current density. The potential is then varied over a range of values and the corresponding corrosion current densities are recorded. The resulting data is then plotted in a Tafel diagram, which visually represents the polarization curves of the sample for both its anodic and cathodic behavior. The anode part of the diagram represents the region where the sample is oxidized, and the cathode part represents the region where the sample is reduced. The slope of the anodic part of the diagram, known as the anodic Tafel slope (β_a), represents the rate at which the anodic reaction increases with increasing potential. Similarly, the slope of the cathodic part of the diagram, known as the cathodic Tafel slope ($-\beta_c$), represents the rate at which the cathodic reaction increases with decreasing potential. The direction of the anode and cathode parts of the diagram depends on the type of corrosion mechanism involved. In general, the anode part of the diagram is oriented towards more positive potentials, while the cathode part is oriented towards more negative potentials. The intersection points of the anode and cathode parts of the diagram, known as the corrosion potential (E_{corr}), represents the equilibrium potential at which the anodic and cathodic reactions are balanced and no net current flows through the sample. The intersection points of the anode and cathode parts of the graph, which is known as the E_{corr}, represents the equilibrium potential where the anode and cathode reactions are balanced and no net current passes through the sample. The j_{corr} is obtained by using this point of intersection. The j_{corr} is a measure of the rate of corrosion on the surface of the sample, expressed in units relative to the area of the surface being evaluated. The results obtained from a Tafel diagram can yield valuable insights about the corrosion behavior of the sample. Lower values of j_{corr} indicate better corrosion resistance and slower corrosion rates, while higher values of j_{corr} indicate higher corrosion rates and poorer corrosion resistance.

Table 2 summarizes The Tafel parameters of TiO_2-epoxy nanocomposite coated pills. Based on the data provided in this table, sample with 0.01 mg TiO_2 has the least j_{corr} among the all samples, with a value of 1.329E-07 mA/cm^2. This indicates that this sample has the best corrosion resistance and lower resistance to corrosion compared to the other samples. This may be attributed to the creation of a protective oxide layer on the sample's surface, which functions as a protection to impede additional corrosion. The higher j_{corr} values of the other samples suggest that they are more susceptible to corrosion and may require additional protective coatings or surface treatments to improve their corrosion resistance. Sample with 0.006 mg TiO_2 has the second-lowest j_{corr} value of 3.643E-06 mA/cm^2, which is lower than the j_{corr} values of Sample with 0.004 and 0.002 mg TiO_2, but higher than that of 0.01 mg TiO_2. The sample with 0.002 mg TiO_2 has the highest amount of corrosion j_{corr}, with a value of 1.98E-04 mA/cm^2, which shows the low resistance of this sample against corrosion among all samples.

Table 2. The Tafel parameters of TiO_2-epoxy nanocomposite coated pills.

Sample	E_{corr}/V	$(j_{corr})_{Tafel}$/mA cm^{-2}	β_a/V dec^{-1}	$-\beta_c$/V dec^{-1}
0.002 mg TiO_2	-0.5476	1.98E-04	0.178	0.211
0.004 mg TiO_2	-0.5697	7.292E-05	0.187	0.178
0.006 mg TiO_2	-0.0971	3.643E-06	0.159	0.154
0.01 mg TiO_2	-0.04391	1.329 E-07	0.155	0.146

4. CONCLUSION

The study aimed to explore the influence of varying quantities of titanium dioxide nanoparticles in epoxy resin on the anti-corrosion characteristics of the TiO_2-epoxy nanocomposite coated pills. Epoxy-TiO_2 nanocomposite coated pills were prepared and subjected to EIS to evaluate their anti-corrosion properties. The results indicated that the sample containing 0.01 mg of TiO_2 exhibited the highest impedance value, indicating superior corrosion resistance and better anti-corrosion properties than the other samples. Additionally, this sample had the lowest corrosion current density among all samples, with a value of 1.329E-07 mA/cm^2, indicating the best corrosion resistance and a slower rate of corrosion compared to the other samples. These findings have implications for the design of more efficient corrosion-resistant materials.

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ДОСЛІДЖЕННЯ ВПЛИВУ КОНЦЕНТРАЦІЇ НАНОЧАСТИНОК TiO_2 НА АНТИКОРОЗІЙНІ ХАРАКТЕРИСТИКИ TiO_2-ЕПОКСИД НАНОКОМПОЗИТНИХ ПОКРИТТІВ

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Вивчені антикорозійні властивості зразків покритих TiO_2-епоксид нанокомпозитами, від концентрації наночастинок TiO_2 в епоксидній смолі. Антикорозійні характеристики зразків досліджували за допомогою електрохімічної імпедансної спектроскопії (EIS). Згідно з результатами EIS, зразок, що містить 0,01 мг TiO_2, продемонстрував найвище значення імпедансу, що вказує на кращу стійкість до корозії та кращі антикорозійні властивості, ніж інші зразки. Крім того, цей зразок має найнижчу щільність струму корозії серед усіх зразків, зі значенням 1,329E-07 мА/см^2, що показує, що цей зразок має найкращу корозійну стійкість і нижчу швидкість корозії порівняно з іншими зразками.

Ключові слова: *епоксидна смола; наночастинки TiO_2; нанокомпозит; електрохімічна імпедансна спектроскопія (EIS); покриття; золь-гель синтез*