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ASSESSMENT OF PROTECTIVE COATINGS FOR CORROSION PREVENTION OF CARBON STEEL IN HIGH-CONCENTRATION SULFURIC ACID ENVIRONMENTS

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ABSTRACT

This study evaluates the performance of three advanced protective coatings—Belzona 4341, Carboline Plasite 4550, and DuraPol UHT—on carbon steel subjected to the aggressive conditions of 98% sulfuric acid. The primary objective is to determine the effectiveness of these coatings in preventing corrosion and extending the lifespan of carbon steel in highly corrosive environments.To achieve this, a series of tests were conducted to assess key performance indicators, including adhesion strength, chemical resistance, hardness retention, and weight loss over time. Adhesion strength was measured to evaluate how well each coating bonded to the carbon steel substrate, which is critical for maintaining protective properties under corrosive conditions. Chemical resistance tests were performed to determine the coatings' ability to withstand the harsh effects of concentrated sulfuric acid, while hardness retention assessments provided insights into the coatings' durability and resistance to mechanical wear. Weight loss measurements were taken to quantify the extent of corrosion that occurred over the testing period.The results of the study revealed that Belzona 4341 outperformed the other coatings in all evaluated parameters, demonstrating superior adhesion strength and exceptional chemical resistance. Additionally, it exhibited minimal weight loss, indicating its effectiveness in preventing corrosion. Carboline Plasite 4550 and DuraPol UHT showed varying degrees of performance, but neither matched the overall effectiveness of Belzona 4341.These findings underscore the importance of selecting appropriate protective coatings for carbon steel in industrial applications, particularly in environments characterized by high acidity. By identifying Belzona 4341 as the most effective solution, this research provides valuable insights for industries seeking to enhance the longevity and reliability of their materials in corrosive settings. The study aims to inform future strategies for corrosion prevention and material selection, ultimately contributing to improved operational efficiency and reduced maintenance costs in industrial applications.

Keywords:*Protective coatings, corrosion resistance, carbon steel, sulfuric acid, Belzona 4341, Carboline Plasite 4550, DuraPol UHT, adhesion strength, chemical resistance, hardness retention, weight loss, industrial application.*

1. Introduction:

The mechanical properties and the cost effectiveness of carbon steel are the important factors increases the industrial application in various sectors. The corrosion becomes severe and challengeable specifically in the petrochemical settings like alkylation units and acid storage tanks while using high concentration of acids like sulfuric acid of 78 - 98 wt%. In this case, the unprotected carbon steel shows the degradation, failure of operations, safety hazard and increases the cost for maintenance [1].

The protecting coatings needs to protect from corrosion in the chemical environments. The coatings prevent the metals from corrosive media which makes the physical and chemical barriers. There are some of the factors which affects the coating efficiency such as chemical resistance, adhesion properties, permeability, and mechanical durability.The selection and the evaluation of the suitable protective coatingsto prevent the materials from high concentration of sulphuric acids.

The phosphate conversion coating in which the iron/ other metal phosphates as a layer to resist corrosion and adhesive for the coating that improves the performance in acidic media [2]. The protection from the acidic media and it was tested by spraying the salt water on the sample. The industries used the fusion bonded epoxy (FBE) to protect the pipelines which forms the barrier layer.The sulfuric acid is used on FBEs protection layer, there is a degradation of the resistance by studying the Electrochemical impedance, the layered system interrupt by using the substrate attack.Ethylene-Chlorotrifluoroethylene (ECTFE) is a electrodeposition of fluropolymer on the steel. ECTFE is especially used to produce sulphuric acid, storage, and flue-gas treatment—attesting to its suitability in high-concentration acid environments. Hybrid organic–inorganic coatings, like GPTMS/APTES, provide barrier protection; solvent choice affects morphology and corrosion resistance[3]. The graphene or graphene oxide are also combined with the polymer resins to improve the properties of the steel as a barrier. Reduced graphene oxides at low charging (0.05 wt%) may be sustained a long-term protection whereas the higher charging caused defects for galvanized steel. The h-BN (hexagonal boron nitride) coatings have emerged as promising electrically insulating barriers, with ongoing research addressing dispersion and defect issues [3].A strong cathodic protection in H_2SO_4 through adsorption and blocking hydrogen evolution can be inhibited by using nitrogen-containing organic inhibitors (e.g., triazole derivatives) in which the efficiency of the inhibition increased by 99%.It has been shown thattriazole derivatives act as complex inhibitors of steel corrosion in sulfuric acid solutions because,along with strong inhibition of metal corrosion, they prevent hydrogen absorption by steel[4].Electrochemical impedance spectroscopy (EIS) and potentiodynamic polarization are key tools to evaluate coating integrity and degradation in sulfuric acid. Surface analysis via SEM, EDX, AFM, Raman, and Tafel curves confirm inhibitor-film coverage, surface morphology changes, and film thickness [5, 6].This paper deals with the performance of different types of coatings with modification to prevent the corrosion of carbon steel from the high concentration acidic environment. The evaluation of the properties of coating such as chemical resistance, adhesion strength, morphological stability, and corrosion inhibition efficiency, that helps in the identification of most effective materials and application strategies for a long-term protection.

The research contribution is to develop more strong, durable and cost-effective materials that prevent the corrosion of industrial equipment in an extreme chemical condition.

2. Materials and Methods

2.1. Materials used: The carbon steel of ASTM A36 grade is used as the substrate. There are three types of coating used such as Belzona 4341 (epoxy-based), Carboline Plasite 4550 (epoxy based), and DuraPol UHT (fluoropolymer-based). The metal after coating tested in presence of 98% sulfuric acid.

2.2. Surface Preparation: The texture of a surface can be measured i.e.surface roughnessusing a profilometer or comparator.It quantifies the peaks and valleys to ensure the surface profile meets specifications for coating adhesion. Adequate roughness enhances mechanical bonding and coating performance.

- Surface Cleanliness: Surface cleanliness assesses the absence of contaminants like oil, grease, or rust on a substrate before coating. Methods include visual inspection, solvent wipe tests, or using specialized equipment. Ensuring cleanliness is critical for adhesion and long-term coating.
- Surface Soluble Salt Contamination: This test detects and quantifies salts, such as chlorides or sulfates, on the surface that can cause coating failures. Techniques like the Bresle method or salt contamination meters measure ion concentration, ensuring the substrate meets permissible levels for optimal coating adhesion and durability.
- Surface Dust Contamination: Surface dust contamination testing identifies particles on a substrate that might affect coating adhesion. Methods include adhesive tape tests or visual inspection under light. Ensuring minimal dust levels prevents defects like pinholes or uneven coating application.

The carbon steel substrates were subjected to abrasive blasting to achieve Sa 2.5 standards, ensuring a surface profile of 50-75 µm for optimal coating The carbon steel substrates were subjected to abrasive blasting to achieve Sa 2.5 standards, ensuring a surface profile of 50-75 µm for optimal coating adhesion. Additionally, the surface was verified to have soluble salt contamination below 20 mg/m² and surface dust contamination at Grade 1, ensuring the required cleanliness and adhesion criteria were met.

3. Coating application involves the controlled application of protective materials to substrates to achieve desired thickness and performance characteristics. The Wet Film Thickness (WFT) refers to the thickness of the coating immediately after application, measured in micrometers (µm). This is a critical parameter, as it ensures that the desired Dry Film Thickness (DFT) is achieved after the coating cures, accounting for solvent evaporation or other factors. Adhering to specified WFT and DFT ranges is essential for optimal coating performance, including corrosion resistance, adhesion, and durability.

Each coating in this evaluation was applied in two uniform layers, with a WFT of 300-400 µm per layer, achieving a DFT of 600-800 µm. The coatings were applied strictly as per their respective product datasheets, ensuring that the application method, curing conditions, and film thickness adhered to the manufacturers' recommendations for optimal performance.

Table. 1. Measurement of DFT value for different areas of the manufacturese

Test Plate #	Point1 in µm	Point2 in µm	Point3 in µm	Point4 in µm	Point5 in µm	Average DFTin µm
Belzona 4341	794	869	819	868	702	874
Carboline Plasite 4550	845	963	846	892	787	975
DuraPol UHT	856	819	891	784	769	1073

4. Results and Discussion

4.1Chemical Resistance:

Immersion Test: The immersion test evaluates a material's ability to resist prolonged exposure to liquids, such as water or chemicals. During this evaluation, specimens were submerged under controlled conditions for **60 days** to observe any changes in weight, appearance, or mechanical properties, which serve as indicators of durability and chemical compatibility. To specifically test chemical resistance, the samples were immersed in **98% sulfuric acid**, one of the most aggressive chemical environments. This rigorous procedure demonstrated the coating's capacity to endure extreme conditions without significant degradation, solidifying its suitability for industrial applications that demand exceptional resilience and long-term performance.

- Belzona 4341 exhibited minimal surface changes, maintaining structural integrity
- Carboline Plasite 4550 displayed moderate resistance, with signs of peeling over time.
- DuraPol UHT showed slight discoloration and lower retention of adhesion properties.

4.2 Visual Test after Chemical Immersion Test:

Comparative Analysis: Visual and numerical data underscore Belzona 4341's superior performance across all evaluated parameters, reaffirming its effectiveness for protecting carbon steel in corrosive environments. It is observed from Fig. 1 that there is a changeincolour,staining,scaledeposition,micro/tinysurfaceblisters,but no sign of corrosion at the edges/corners of the plate#1. The observations found in other plates are such as in plate#2, there is a changeincolour,staining,scaledeposition, surfaceblisters,coating damage andcorrosion at the edges/corners of the plate; whereas in plate # 3, there is a changeincolour,staining,scaledeposition,surfaceblisters,coating damage andcorrosion at the edges/corners of the plate.

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Plate # 1 (Belzona 4341) | Plate # 2 (Carboline Plasite 4550) | Plate # 3 (DuraPol UHT)

Fig. 1 Visual Test after immersion test in 98% Sulphuric acid

4.3 Electrochemical Impedance Spectroscopy (EIS) Test:

Electrochemical Impedance Spectroscopy (EIS) is a powerful technique used to measure the electrochemical properties of materials by applying an alternating current and analyzing the impedance response over a range of frequencies. This method provides insights into corrosion resistance, coating performance, and the long-term condition of protective barriers.

In this evaluation, specimens coated with Belzona 4341, Carboline Plasite 4550, and DuraPol UHT were subjected to EIS testing. The results revealed that Belzona 4341 exhibited the highest corrosion resistance among the three coatings. The impedance modulus at low frequency ($|Z|0.1$ Hz), a critical indicator of barrier performance, was significantly higher for Belzona 4341 at 4.2×10^9 $\Omega\cdot cm^2$ compared to Carboline Plasite 4550 (2.8×10^8 $\Omega\cdot cm^2$) and DuraPol UHT (1.6×10^7 $\Omega\cdot cm^2$).

Additionally, the phase angle measurements indicated superior barrier properties for Belzona 4341, with minimal phase angle deviations over time, suggesting stable and long-lasting corrosion protection. Both Carboline Plasite 4550 and DuraPol UHT showed noticeable decreases in impedance and phase angle stability, indicating reduced performance under prolonged exposure to corrosive environments.

These findings underscore Belzona 4341's exceptional ability to maintain a robust protective barrier and resist corrosion effectively, making it the preferred choice for applications in highly aggressive chemical environments such as 98% sulfuric acid. Its superior performance compared to the alternative coatings highlights its reliability and durability in demanding industrial conditions.

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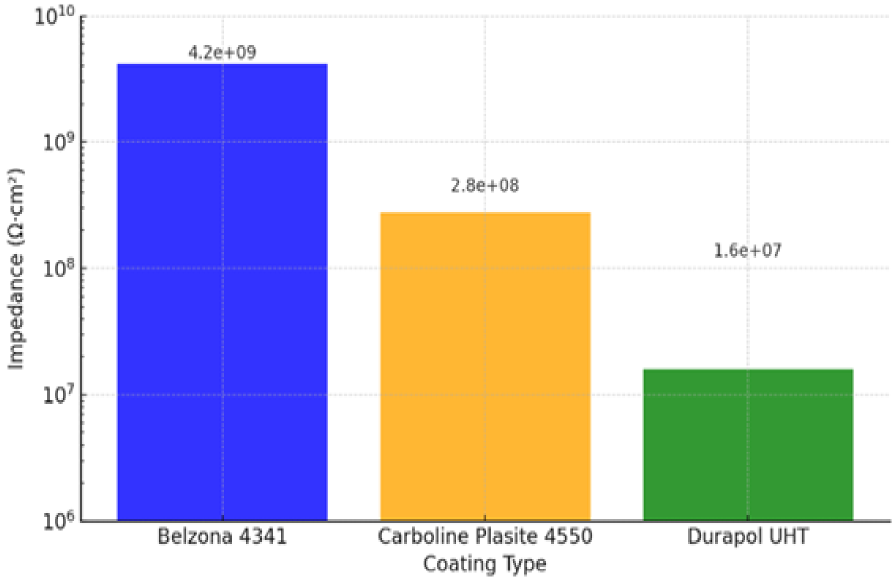

Fig. 2EIS values at low frequency (|Z| 0.1 Hz)

4.3 Hardness Retention:

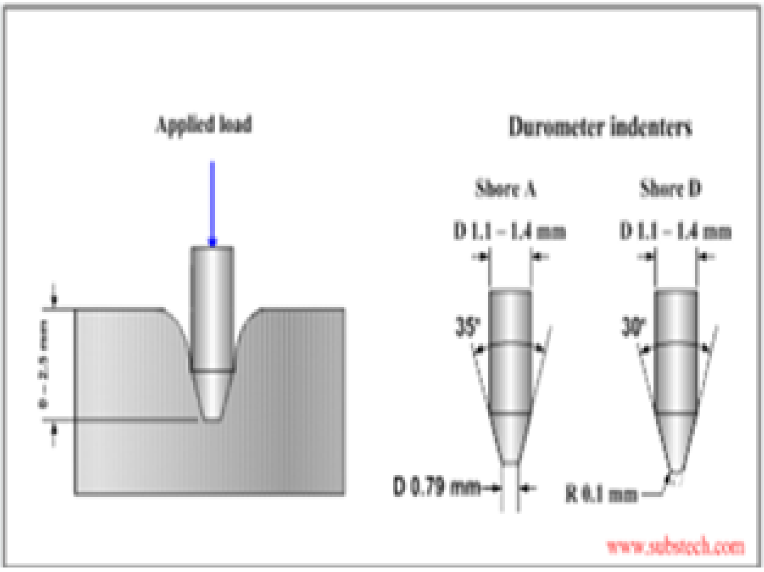

Fig. 3 Durometer hardness test

Shore D Hardness Test: The Shore D hardness test measures the hardness of hard plastics or coatings using a durometer. A standardized needle presses into the material under specified force, and the resistance is recorded on a scale, providing an indicator of surface hardness and rigidity

- Belzona 4341 retained 95% of its original Shore D hardness values.
- Carboline Plasite 4550 retained 82%,
- DuraPol UHT retained 75%.

4.4 Weight Loss:

The weight loss test is a widely used method to assess the corrosion resistance of materials and coatings. In this test, specimens are subjected to a corrosive environment for a defined period under controlled conditions. Each specimen’s initial weight is recorded before exposure. After the test, the specimens are cleaned to remove any corrosion products, and their final weights are measured. The difference between the initial and final weights reflects the material's or coating's resistance to corrosion, with a lower weight loss indicating superior protection and durability.

In this study, weight loss tests were performed on specimens coated with Belzona 4341, Carboline Plasite 4550, and DuraPol UHT. The results revealed that Belzona 4341 exhibited the lowest weight loss, highlighting its superior corrosion resistance. Below are the recorded weight loss values:

- Belzona 4341 demonstrated the least material loss at 74 g.
- Carboline Plasite 4550 losses of 109 g
- DuraPol UHT recorded higher 205 g

These findings clearly demonstrate that Belzona 4341 outperforms the other coatings in protecting the substrate from corrosion. Its significantly lower weight loss underscores its effectiveness in minimizing material degradation, making it a highly dependable option for applications in extremely corrosive environments, such as exposure to 98% sulfuric acid. This performance not only enhances the longevity of the coated components but also reduces maintenance and replacement costs in demanding industrial settings.

4.5 DFT (Dry Film Thickness) Test:

This test measures the thickness of coatings applied to the surface, typically using non-destructive techniques like magnetic gauges or ultrasonic devices. Accurate thickness measurement ensures adequate coverage for protection, durability, and compliance with standards.

- The dry film thickness (DFT) of the coatings was measured before and after immersion testing to evaluate their stability under the influence of 98% sulfuric acid. The initial DFT for all coatings was within the range of 300–400 µm, as applied per standard procedures. After 60 days of immersion:
- Belzona 4341 retained an average DFT of 98%, with minor variations attributed to localized surface degradation. This minimal reduction indicates strong barrier properties and resistance to acid penetration.
- Carboline Plasite 4550 exhibited an 8% reduction in DFT, suggesting moderate deterioration, likely due to its partial peeling during immersion.
- DuraPol UHT showed the highest reduction, retaining only 85% of the original DFT, highlighting its comparatively lower acid resistance.
- These findings correlate with the superior chemical resistance and adhesion properties of Belzona 4341, further emphasizing its suitability for highly corrosive environments.

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Table. 1. Measurement of DFT value for different areas of the manufacturese

Test Plate #	Point1 DFT in µm	Point2 DFT in µm	Point3 DFT in µm	Point4 DFT in µm	Point5 DFT in µm	Average DFT in µm
1	860	937	872	968	734	874
2	1022	1101	908	983	859	975
3	1306	1029	1154	892	985	1073

Fig. 4. Observation of DFT for three plates

Plate # 1 (Belzona 4341) | Plate # 2 (Carboline Plasite 4550) | Plate # 3 (DuraPol UHT)

4.6 Holiday Test:

The holiday test detects pinholes or discontinuities in non-conductive coatings applied to conductive substrates. A voltage is applied across the coating; any flaw allowing current to pass is identified as a "holiday," ensuring complete coverage.

Holiday testing was conducted pre- and post-immersion to assess the integrity of the coatings. Before immersion, all coatings passed the continuity test, indicating defect-free applications. Post-immersion results showed:

- Belzona 4341 retained complete continuity, with no detectable holidays, confirming its robust performance under corrosive conditions.
- Carboline Plasite 4550 exhibited minor discontinuities, with a holiday detection rate of 5%, likely arising from surface peeling and microcracking.
- DuraPol UHT demonstrated the highest holiday detection rate at 12%, indicating significant loss of continuity, consistent with its lower adhesion strength and chemical resistance.

		
Belzona 4341	Carboline Plasite 4550	DuraPol UHT

Fig.5 Holiday Test for three plates

- Test Method: High Voltage Spark Test
- Test Voltage: 3000 Volts DC
- Test Results: No holidays were detected on Plate #1 (coated with Belzona 4341). In contrast, multiple holidays and blisters were observed on Plate #2 (coated with Carboline Plasite 4550) and Plate #3 (coated with Durapol UHT).

4.7 Pull-off Adhesion Test:

This test assesses the adhesive strength of a coating by attaching a dolly to the surface and applying tensile force until the coating detaches. The force required to remove the coating provides a measure of bond strength to the substrate.

Values recorded after Pull-off Adhesion Test

- Belzona 4341 achieved the highest adhesion strength, measuring 2206 Psi (15.2 MPa).
- Carboline Plasite 4550 recorded 1275 Psi (8.7 MPa)
- DuraPol UHT demonstrated 1050 Psi (7.2 MPa.)

		
Belzona 4341	Carboline Plasite 4550	DuraPol UHT

Fig.6 Test results of Holiday Test for three plates

Conclusion

The evaluation identifies **Belzona 4341** as the most effective coating for carbon steel exposed to environments containing 98% sulfuric acid. This conclusion is based on its exceptional performance across key parameters such as **adhesion strength**, **chemical resistance**, and **hardness retention**, which are critical for ensuring long-term material durability in highly corrosive conditions.

Adhesion strength is a decisive factor in maintaining the integrity of coatings under mechanical stress and chemical exposure. Belzona 4341 demonstrates superior adhesion, minimizing the risk of delamination or peeling even in extreme acid environments. This robust adhesion ensures that the coating remains firmly bonded to the carbon steel surface, providing continuous protection against chemical attack.

Chemical resistance is another key attribute of Belzona 4341. The coating exhibits remarkable stability and resistance to sulfuric acid, preventing degradation, blistering, or erosion over prolonged exposure. This resistance enhances the lifespan of the protected material, reducing maintenance frequency and downtime in industrial operations.

Additionally, the **hardness retention** of Belzona 4341 under these harsh conditions underscores its mechanical resilience. The coating maintains its structural integrity and resists physical wear, further solidifying its role as a dependable protective solution.

These combined qualities make Belzona 4341 an excellent choice for industrial applications that require reliable protection in highly aggressive chemical environments. Its ability to withstand the extreme corrosive nature of 98% sulfuric acid ensures minimal material loss and operational disruptions, translating to enhanced efficiency and cost-effectiveness for industrial processes.

In conclusion, the findings validate Belzona 4341 as a reliable and high-performance coating for carbon steel in extreme sulfuric acid conditions, making it an indispensable solution for industries demanding unparalleled chemical resilience and mechanical durability.

Recommendations

- Field trials have to be implemented to validate the laboratory findings under real-world conditions.
- A cost-benefit analysis has to be performed to determine the feasibility of large-scale adoption.
- Investigate potential enhancements to Belzona 4341's formulation for even greater durability in harsh environments.

Acknowledgement:

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   [3] DuraPol UHT
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