

Article

Analysis of Coating Failure in Hainan's Coastal Atmospheric Environment and Correlation Between Indoor and Outdoor Testing

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Abstract

This study investigated the degradation behavior of a polyurethane acrylate coating/Q345B steel system under the coastal atmospheric conditions of Wenchang, Hainan, and evaluated the correlation between indoor accelerated tests and outdoor exposure. Outdoor exposure tests, single-factor accelerated tests (UV irradiation and neutral salt spray), and a multi-factor cyclic accelerated test combining UV, salt spray, humidity, and thermal cycling were conducted. Coating degradation was characterized by morphological observation, gloss measurement, adhesion testing, and electrochemical impedance spectroscopy. The results showed that after 8 months of outdoor exposure, localized rust spots, blistering, and under-film corrosion appeared on the coating surface. The gloss loss rate reached 15.72% after 3 months, while adhesion decreased from 5.83 MPa to 2.39 MPa during prolonged exposure. UV irradiation mainly affected gloss degradation, whereas corrosive media penetration played a dominant role in adhesion loss and electrochemical deterioration. Compared with single-factor tests, the multi-factor cyclic accelerated test exhibited the highest correlation with outdoor exposure. The corresponding correlation coefficients for gloss loss, adhesion, and low-frequency impedance modulus were 0.9764, 0.9988, and 0.9929, respectively, while the gray relational coefficients reached 0.8334, 0.8467, and 0.7977. These results demonstrate that the multi-factor cyclic accelerated test more accurately reproduces the degradation behavior and failure characteristics observed in the coastal atmosphere of Hainan. The proposed method provides a practical approach for indoor–outdoor correlation analysis and durability evaluation of protective coatings in marine atmospheric environments.

Keywords: polyurethane acrylate coating; corrosion; outdoor exposure; indoor–outdoor correlation; accelerated aging



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1. Introduction

Metal corrosion, as a critical issue constraining modern industrial development, directly impacts the service life of engineering materials through its protective efficacy. In marine atmospheric environments, organic coating protection systems have become the preferred solution for metal substrate corrosion protection due to their excellent barrier properties and cost-effectiveness [1–4]. However, prolonged exposure to harsh conditions—including high salt fog, intense ultraviolet radiation, and alternating wet and dry heat—can induce synergistic degradation through photo-oxygen aging and hydrolysis. This leads to deterioration of the coating's physicochemical properties, failure of interfacial adhesion, and ultimately loss of corrosion protection functionality.

In studying coating aging mechanisms, Armstrong et al. [5] pioneered the theory of UV-induced radical chain reactions, systematically revealing the competitive mechanism between main-chain scission and crosslinking reactions in coatings. Building upon this theoretical framework, subsequent scholars [6–13] progressively elucidated the photodegradation kinetics of various resin systems (polyurethane–acrylic [10] and phenoxy resin [13]), discovering that polyurea systems exhibit unique insensitivity to UV irradiation due to their super-elastic structure [12]. Notably, hydrolysis—a failure pathway equally significant to photodegradation—exhibits pronounced chemical selectivity: polar groups like ester and urethane bonds undergo preferential cleavage under water penetration [14,15], while loosely cured structural regions become more susceptible to hydrolysis [16,17]. Research confirms that water reacts with easily hydrolyzed groups on the coating surface or within the interior. The hydrolysis tendency of functional groups like esters, ureas, ethers, alcohols, and amines gradually decreases. Post-reaction, molecular chains in the coating fracture, leading to coating aging and failure [18,19]. The wet/heat synergistic environment significantly accelerates microcrack initiation and propagation by inducing swelling-shrinkage cyclic stresses in coatings [20–22]. Furthermore, the dynamic transport behavior of chloride ions at the metal/coating interface has been identified as a key factor controlling interfacial delamination [23]. The ion diffusion suppression effect exhibited by multilayer coating structures offers new insights for enhancing the durability of protective systems [24].

Current coating evaluation systems exhibit two major trends: First, field exposure tests, leveraging their environmental authenticity, have yielded significant results in typical climate zone studies. For instance, Yang et al. [25] revealed the accelerated degradation effect of high-altitude intense radiation on polyurethane–acrylic coatings, while Fang et al. [26] systematically elucidated the differential failure patterns of H53 coatings under multiple climate modes, including tropical marine and plateau environments. Jorcin et al. [27] developed a kinetic model for steel/epoxy-vinyl primer interface delamination based on single salt spray testing. Yu Junfeng et al. [28] utilized salt spray tests to simulate coastal atmospheric corrosion environments for studying nano-TiO₂-modified epoxy zinc-rich coatings. Second, addressing limitations of traditional single-factor accelerated testing, multi-factor coupled acceleration methods are progressively being refined. Wang et al. [29] first identified the shortcomings of polyurea systems in resisting Cl[−] permeation under extreme conditions through UV–salt spray–temperature cycling tests. Yu et al. [30] employed alternating cycles of UV irradiation, salt spray, and thermal shock to simulate Arctic coastal conditions. All coatings exhibited accelerated degradation under combined UV–salt spray–low-temperature exposure compared to isolated low-temperature or UV environments, demonstrating synergistic acceleration of coating failure by environmental factors. Yuan Min et al. [31] designed a multi-factor laboratory accelerated simulation method targeting tropical marine environments, combining solar irradiation, high temperature, high humidity, and salt spray. Test results under multi-factor conditions showed more pronounced regularity, correlation, and acceleration than single-factor tests, demonstrating higher relevance to natural environment outcomes.

For coating systems, developing indoor accelerated testing methods with strong correlation to outdoor environmental testing is crucial for shortening new coating development cycles and evaluating service life. Consequently, numerous scholars worldwide have proposed various approaches to study indoor–outdoor correlation. Wang Pengfei et al. [22] conducted a comprehensive quantitative assessment of coating aging damage by considering multiple properties and characteristics of coating aging. They ultimately employed curve fitting to determine the variation patterns of coating aging damage and the correlation between indoor and outdoor tests. Gao et al. [32] designed a multi-factor accelerated test for marine atmospheric environments to address the physicochemical multi-field coupling

effects on anti-corrosion coatings. They quantitatively analyzed the correlation among the aging curves of three environmentally friendly coatings, demonstrating that multi-factor accelerated testing exhibits higher correlation with outdoor exposure tests. Deng Liang et al. [33] employed gray relational analysis to validate the significant superiority of multi-factor accelerated testing over single-factor testing in simulating real marine environments. However, existing research still exhibits notable deficiencies in targeted simulation for tropical coastal climates and quantitative mapping of indoor–outdoor aging pathways.

This study investigates the failure behavior and degradation mechanisms of a polyurethane acrylate coating/Q345B steel system exposed to the coastal atmospheric environment of Wenchang, Hainan. A single-layer transparent coating system was intentionally adopted as a simplified model coating system to minimize the interference of pigments, fillers, and multilayer interfaces, thereby enabling direct observation of photo-oxidative degradation, hydrolysis, interfacial delamination, and corrosive media penetration during aging. Such a model system is particularly suitable for clarifying environmental coupling effects and establishing indoor–outdoor correlation relationships in accelerated aging studies. However, it should also be noted that the present coating configuration does not fully represent practical heavy-duty multilayer protective systems containing anticorrosive pigments or complex interlayer structures. Therefore, the conclusions of this work are mainly applicable to degradation mechanism analysis and accelerated test methodology development, while further validation on industrial multilayer coating systems is still required. Based on this model system, standalone UV irradiation tests, neutral salt spray tests, and multi-factor cyclic indoor accelerated tests were comparatively conducted to identify the dominant factors governing coating degradation and to evaluate the feasibility of the proposed multi-factor accelerated testing protocol.

2. Experimental Methods

2.1. Material

The coated specimens used Q345B steel as the metal substrate. The substrate was cut into different dimensions using wire cutting: electrochemical specimens measured 10 mm × 10 mm × 2 mm (Table 1), outdoor exposure test specimens measured 150 mm × 75 mm × 2 mm, and indoor accelerated test specimens measured 60 mm × 40 mm × 2 mm. All specimens for indoor and outdoor testing underwent sand-blasting to achieve a surface rust removal grade Sa2.5. After the surface treatment dried, coatings were sprayed with an approximate thickness of 50 µm. All coated specimens were sealed along their four edges and on the reverse side using 3M adhesive tape. Sealing at the joints was performed with silicone sealant. The adhesive tape was positioned 5 mm from the specimen edges. Specimen numbers were written on the reverse side using a marker pen before storage.

Table 1. Coating sample-related parameters.

Substrate	Coating	Coating Composition
Q345B	Polyurethane–acrylic varnish	Hydroxyacrylic resin content: 80–85%, additives: 1%, and solvent content: 10–15%; blended with polyurethane curing agent.

2.2. Methods

2.2.1. Indoor Accelerated Test

Multi-factor cyclic accelerated testing: Based on meteorological and environmental data from Wenchang, Hainan, in 2020, an environmental spectrum was established using equivalent corrosion and equivalent aging design principles to conduct indoor accelerated

testing. The test process is shown in Figure 1. One complete cycle of the test process constitutes one test period. Test periods 1, 2, 3, and 4 each involved six parallel specimens: four specimens with intact coatings and two specimens with cross-scratched coatings.

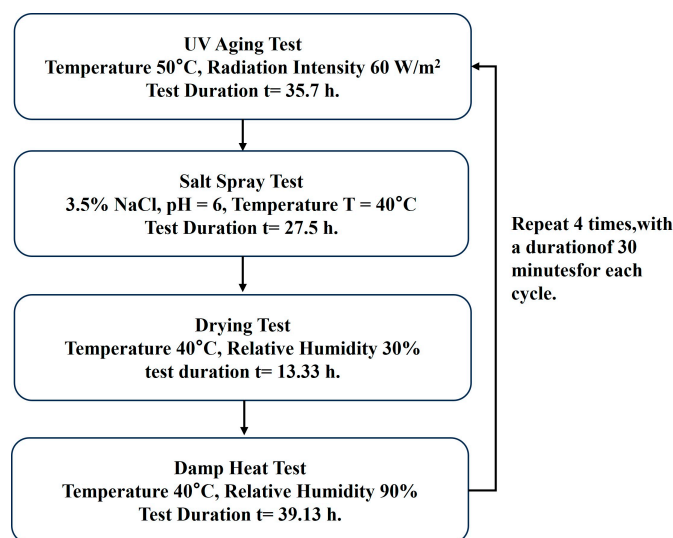


Figure 1. Indoor coupled accelerated testing.

UV Aging Test: Following GB/T 31881-2015 [34] “Accelerated UV Aging Test Method for Non-metallic Components and Materials of Automobiles,” test parameters were set as: UVA lamp, wavelength 340 nm, test temperature 50 °C. Sampling intervals matched those of the multi-factor cyclic accelerated test.

Neutral salt spray test: Following the neutral salt spray test method in GB/T 10125-2021 [35] “Corrosion Tests in Artificial Atmospheres-Salt Spray Test,” salt spray exposure was simulated using continuous spraying. The salt solution consists of (5 ± 0.5) wt% NaCl with a pH of 6.5–7.2. The test temperature was 35 ± 2 °C. The salt spray deposition rate was $(1\sim3)$ mL/(80 cm²·h). Samples were removed for testing and analysis at specified intervals. Sampling intervals are the same as for the multi-factor cyclic accelerated test.

2.2.2. Outdoor Exposure Test

The outdoor exposure testing site was selected in Wenchang, Hainan. Samples were submitted to the Wenchang Atmospheric Exposure Testing Station in Hainan in accordance with the reference standard GB/T 9276-1996 “Methods for Natural Climate Exposure Testing of Coatings.” Exposure cycles lasted 3 months, 6 months, and 8 months, respectively, with a sun exposure angle of 45°.

2.2.3. Surface Morphology Characterization

Digital photography was employed to observe the macroscopic morphology of the intact coating. A 3D confocal microscope was utilized to examine the delamination morphology of coating specimens. Analysis software such as VK-X Series and MultiFileAnalyzer 1.1.20.83 was applied to analyze the 3D morphology of the coating surface, including surface topography and height variations. Observations were conducted using an FEI Quanta 250 environmental scanning electron microscope (FEI Company, Hillsboro, OR, USA) and an AMETEK-19-EDAX energy dispersive X-ray spectrometer (EDAX Inc., Mahwah, NJ, USA).

2.2.4. Coating Performance Test Methods

Refer to GB/T 9754-1988 for determining the gloss of paint films before and after aging using the XGP series portable specular gloss meter. Employ the PosiTest pull-off

adhesion tester from DeFelsko Corporation (Ogdensburg, NY, USA) to assess the bond strength between the coating and the metal substrate, with a 20 mm diameter indenter.

2.2.5. Electrochemical Tests

The CS310M electrochemical work station, manufactured by Wuhan KESTE Instrument Co., Ltd. (Wuhan, China), was employed. A classic three-electrode system was utilized, featuring a platinum sheet as the auxiliary electrode, a saturated calomel electrode (SCE) as the reference electrode, and the coated sample as the working electrode. The electrolyte solution consisted of a 3.5% NaCl solution. The test frequency range spanned from 10^5 Hz to 10^{-2} Hz, with a sinusoidal excitation signal amplitude of 15 mV. Impedance data is analyzed using ZSimpWin 3.60 software.

3. Results

3.1. Analysis of Outdoor Exposure Coating Failure

3.1.1. Surface Morphology Analysis

As clearly shown in Figure 2, the polyurethane–acrylic coating samples exhibited a smooth and flat surface with a colorless, transparent coating prior to outdoor exposure. After 3 and 6 months of outdoor exposure, the coating showed no significant changes, with only slight variations in surface roughness. After 8 months of outdoor exposure, rust spots of varying sizes appeared under the coating in some areas, distributed sporadically.

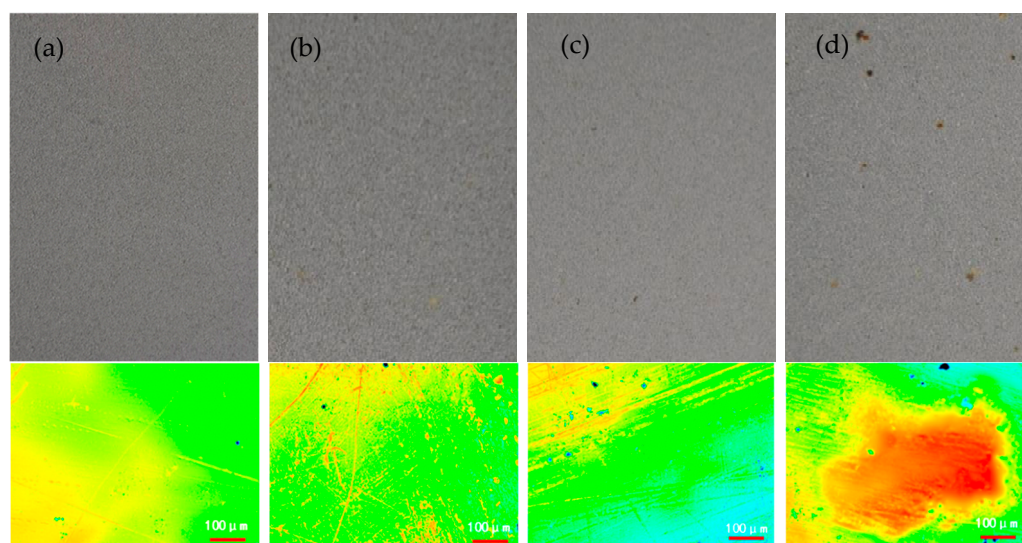


Figure 2. Surface morphology of polyurethane–acrylic coating after different exposure times outdoors (top: macro morphology; bottom: 3D morphology). (a) Original; (b) 3 months; (c) 6 months; (d) 8 months.

As clearly shown in the figure, the surface of the polyurethane–acrylic coating sample was smooth and flat before outdoor exposure, with a colorless and transparent coating. After 3 and 6 months of outdoor exposure, the coating showed no significant changes, with only slight variations in surface roughness. After 8 months of outdoor exposure, rust spots appeared under the coating in some areas, varying in size and distributed sporadically.

3.1.2. Degradation of Gloss and Adhesion

As shown in Figure 3, the gloss of the polyurethane–acrylic coating gradually decreased with increasing test duration. Prior to 6 months of outdoor exposure, the coating's gloss declined rapidly; after 6 months of outdoor exposure, the rate of gloss reduction slowed. Additionally, the gloss loss rate of the polyurethane–acrylic coating gradually

increased with extended test duration. After 3 months of outdoor exposure, the coating's gloss loss rate was 15.72%. According to the coating gloss loss grading in the "Rating Method for Aging of Paint and Varnish Coatings," this is classified as very slight gloss loss. After 6 and 8 months of outdoor exposure, the coating's gloss loss rates were both between 16% and 30%, classified as slight gloss loss. In the atmospheric environment of Wenchang, despite relatively intense ultraviolet radiation, the polyurethane–acrylic coating demonstrated good resistance to UV irradiation, resulting in a lower loss of gloss.

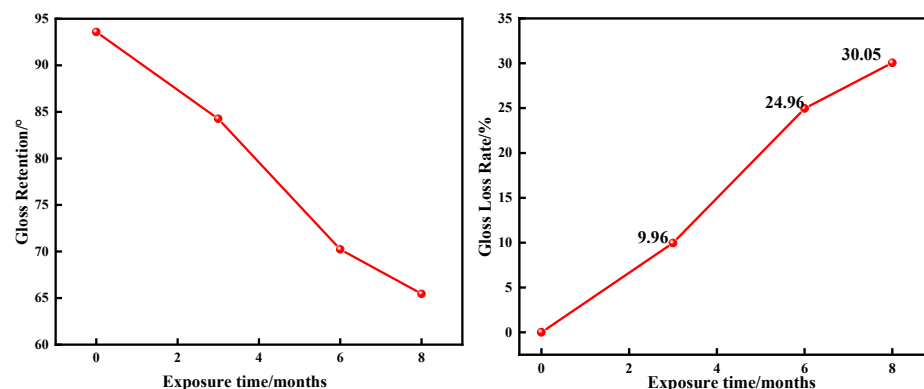


Figure 3. Gloss retention and gloss loss rate of polyurethane–acrylic coatings after different durations of outdoor exposure.

As shown in Figure 4, the adhesion of polyurethane–acrylic coatings gradually decreases with prolonged outdoor exposure, dropping from 5.83 MPa to 2.39 MPa. Prior to six months of outdoor exposure, adhesion changes remain relatively minor, but after six months, the rate of change accelerates significantly, with an adhesion loss rate reaching 59%. Based on the results of both macro- and micro-morphology analysis, for polyurethane–acrylic coatings, the annual average atmospheric humidity in Wenchang is 85%. High humidity causes moisture to gradually penetrate into the polyurethane–acrylic coating. Before six months of outdoor exposure, moisture had not yet permeated to the organic coating/metal interface, resulting in minimal adhesion loss. However, after six months of outdoor exposure, moisture gradually penetrated to the interface, triggering electrochemical corrosion reactions that reduced the bond strength between the coating and the metal substrate, leading to a sustained decline in coating adhesion.

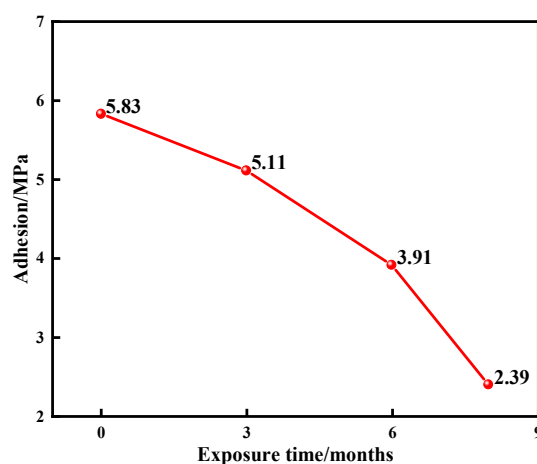


Figure 4. Changes in adhesion of polyurethane–acrylic coatings after different durations of outdoor exposure.

3.1.3. Electrochemical Behavior

As shown in Figure 5, for the original polyurethane–acrylic coating sample, the low-frequency impedance membrane value at 0.01 Hz is approximately $10^{10} \Omega \cdot \text{cm}^2$. The capacitive arc in the Nyquist plot forms a large semicircle, exhibiting a single time constant. This behavior indicates an excellent barrier layer capable of protecting the metal substrate from corrosion. After 3 and 6 months of outdoor exposure, the low-frequency impedance membrane value decreased to $10^9 \Omega \cdot \text{cm}^2$, with the radius of the capacitive arc in the Nyquist plot noticeably shrinking. However, it still exhibited a time constant, indicating the coating remained effective at isolating moisture. At this stage, moisture was permeating but had not yet reached the metal interface. After 8 months of outdoor exposure, the low-frequency impedance film value decreased to $1.09 \times 10^9 \Omega \cdot \text{cm}^2$. While impedance remained relatively high, rust spots appeared. The capacitive arc in the Nyquist plot exhibited two time constants, indicating that moisture and other corrosive media had reached the metal interface, triggering electrochemical corrosion reactions.

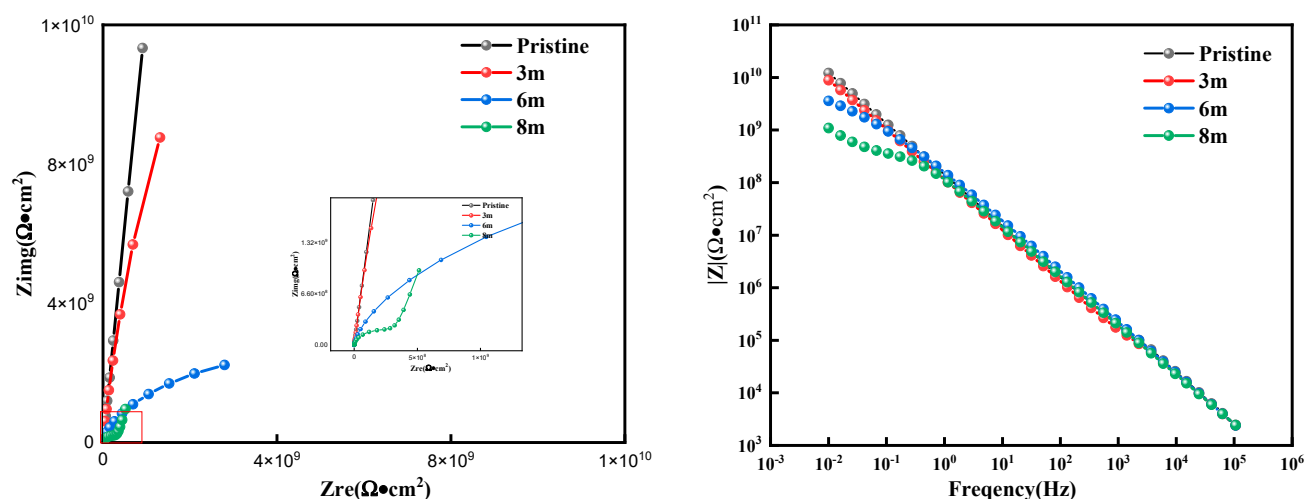


Figure 5. Electrochemical spectra of polyurethane–acrylic coatings exposed outdoors for varying durations ((left): Nyquist plot; and (right): Bode plot).

3.2. Coating Degradation Under Laboratory Accelerated Tests

3.2.1. Comparison of Failure Modes Across Test Conditions

The macroscopic morphology of polyurethane–acrylic coating specimens under different test conditions is shown in Figure 6. It is evident that initially, the coating surface is smooth and flat, appearing colorless and transparent. Under ultraviolet irradiation testing, the polyurethane–acrylic coating maintains a relatively smooth and flat surface, though it loses slight gloss. Under salt spray test conditions, blistering appeared on the coating in the third cycle, with bubbles significantly enlarging by the fourth cycle. Under multi-factor cyclic accelerated test conditions, the coating surface roughness increased slightly, with localized rusting occurring in the third cycle and becoming more pronounced by the fourth cycle.

Laser confocal images reveal that prior to testing, the polyurethane–acrylic coating surface was relatively smooth and flat. Under UV test conditions, the coating surface remained largely flat by the fourth cycle, with only a slight increase in roughness. Under salt spray test conditions and multi-factor cyclic accelerated test conditions, the coating exhibited significant underfilm corrosion.

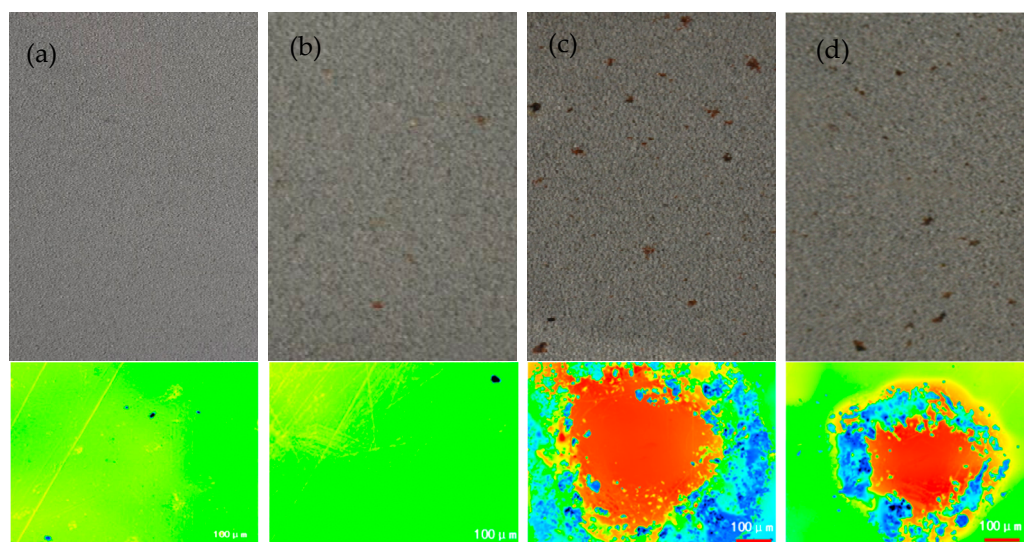


Figure 6. Surface morphology of polyurethane and acrylic coatings after four cycles under different test conditions. (a) Original; (b) UV exposure; (c) salt spray; (d) multi-factor cycling.

3.2.2. Comparative Analysis of Gloss and Adhesion

As shown in Figure 7, the gloss loss rate of the polyurethane–acrylic coating gradually increases with extended test duration. Among the test conditions, ultraviolet irradiation has the most significant impact on the gloss loss rate of the epoxy resin coating, while salt spray has the least effect. The multi-factor cyclic accelerated test falls between these two extremes. Based on the gloss loss rating scale, the polyurethane–acrylic coating exhibited a gloss loss rate of 31–50% during the fourth cycle of UV irradiation testing, classified as significant gloss loss. Coatings subjected to the multi-factor cyclic accelerated test showed a gloss loss rate of 16–30%, categorized as slight gloss loss. Coatings tested under salt spray conditions demonstrated a gloss loss rate of 4–15%, classified as very slight gloss loss. Initially, the coating surface was relatively smooth with high gloss. However, as testing progressed, environmental factors affected the coating. The salt spray test, lacking UV irradiation, did not cause significant changes in gloss. Nevertheless, the accumulation of corrosive media on the coating surface altered its smoothness, leading to slight gloss loss. In both the UV irradiation test and the multi-factor cyclic accelerated test, the loss of gloss initially increased slowly before accelerating rapidly, showing consistent trends. UV irradiation caused molecular degradation, increasing the surface roughness of the coating. However, the multi-factor cyclic accelerated test involved shorter UV exposure times, resulting in a milder loss of gloss and better simulation performance.

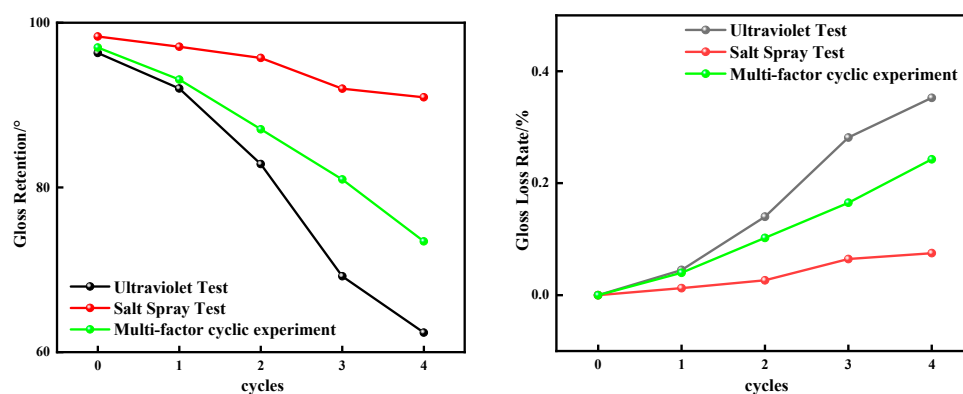


Figure 7. Gloss and gloss loss rate of polyurethane–acrylic coating under different test conditions and cycles.

As shown in Figure 8, the adhesion of the polyurethane–acrylic/Q345B steel system gradually decreased with extended indoor testing duration. Both the multifactor cyclic accelerated test and the neutral salt spray test exhibited similar trends in their impact on coating adhesion, decreasing from approximately 6 MPa to around 1 MPa. Under the single ultraviolet irradiation test, coating adhesion slowly declined to about 5 MPa. In the multifactor cyclic accelerated test and neutral salt spray test, the polyurethane–acrylic coating exhibited significant susceptibility to corrosion medium penetration. The corrosive medium slowly infiltrated into the coating’s interior, causing a gradual decline in adhesion. During the intermediate phase, as the corrosive medium penetrated to the interface, adhesion decreased rapidly. In the later phase, corrosion products formed, slowing the rate of adhesion loss. Under single UV irradiation, adhesion loss was gradual, indicating that UV radiation has a limited effect on polyurethane–acrylic coatings, resulting in minimal adhesion loss.

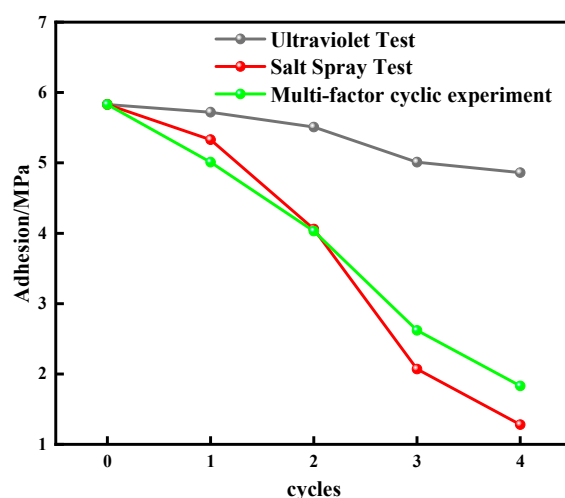


Figure 8. Adhesion of polyurethane–acrylic coating at different test conditions and cycles.

3.2.3. Comparative Electrochemical Behavior

Figures 9–11 reveal that the electrochemical impedance spectra of polyurethane–acrylic coatings exhibit identical patterns of change under ultraviolet irradiation, neutral salt spray, and multi-factor cyclic accelerated testing. This aligns with the aging failure mechanism observed in outdoor environments, where the aging process is divided into three stages: early, mid, and late aging. However, in salt spray testing, impedance values decline more rapidly, with a higher incidence of rust spots beneath the coating film. The aging failure process is divided into three stages: early aging, mid-aging, and late aging. However, in the salt spray test aging process, the impedance value decreases more rapidly, and there are more rust spots under the coating film. In the multi-factor cyclic accelerated test, the impedance value decreases slightly more slowly. Nevertheless, due to the presence of ultraviolet irradiation, it effectively combines the combined effects of ultraviolet light and salt spray, possessing both accelerated and relevant characteristics, and well mimics the actual outdoor conditions. In UV irradiation tests, corrosive media like moisture, chloride ions, and oxygen are minimal. The Nyquist plots for the coating across cycles 0, 1, 2, 3, and 4 all exhibit a single time constant, with the radius of the capacitive arc gradually decreasing. Concurrently, the electrochemical impedance membrane value diminishes but remains above $10^9 \Omega \cdot \text{cm}^2$, indicating the polyurethane–acrylic coating exhibits strong resistance to UV irradiation. Short-term UV exposure causes only minor aging and degradation of the coating.

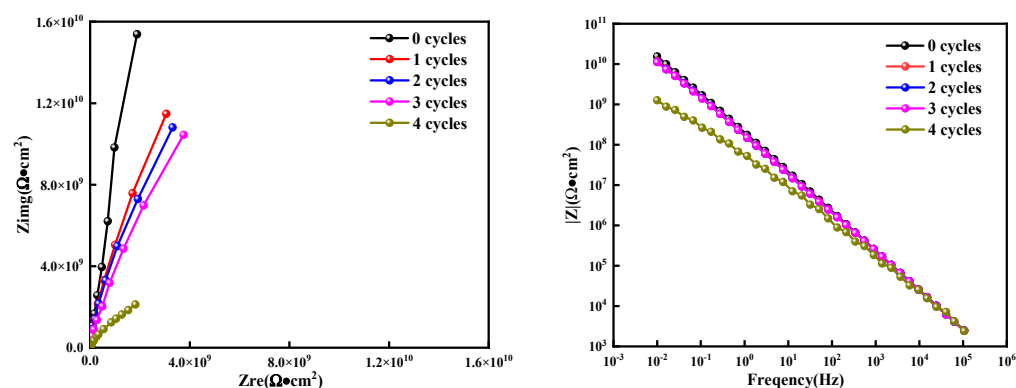


Figure 9. Cyclic AC impedance of polyurethane–acrylic coating under UV test conditions.

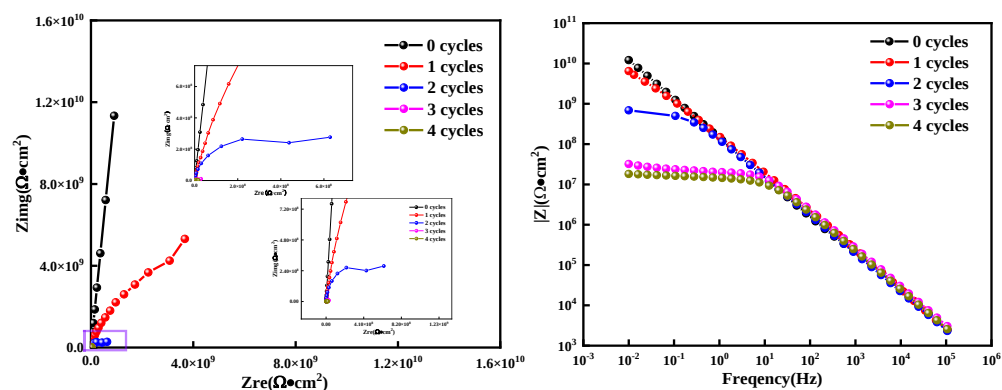


Figure 10. Cyclic AC impedance of polyurethane–acrylic coating under salt spray test conditions ((left): Nyquist plot; (right): Bode plot).

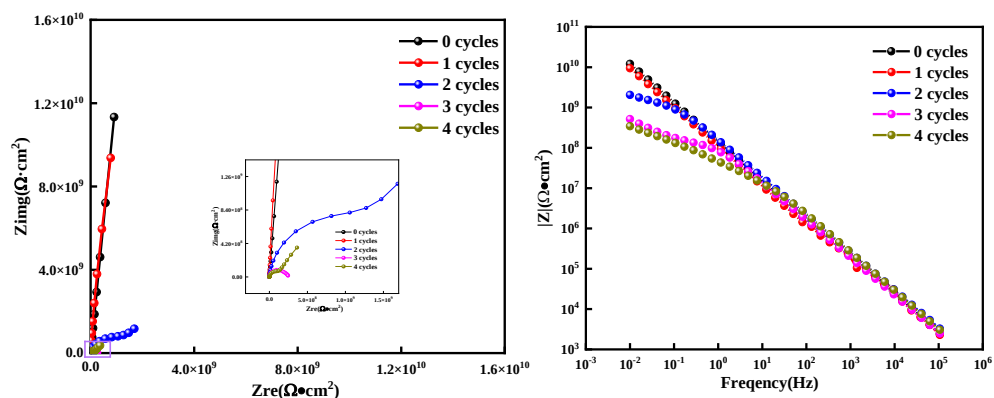


Figure 11. Alternating-current impedance at different cycles under multi-factor cyclic test conditions for polyurethane–acrylic coatings ((left): Nyquist plot; (right): Bode plot).

3.3. Indoor–Outdoor Correlation Analysis

3.3.1. Qualitative Correlation via Performance Trend Analysis

The changes in gloss loss, adhesion, and low-frequency impedance modulus of organic coating systems respectively reflect alterations in surface properties, interfacial properties, and electrochemical properties. This section employs these three parameters to perform correlation analysis on the failure behavior of polyurethane–acrylic coating/Q345B steel systems through curve fitting methods. The analyses cover multi-factor cyclic accelerated testing, single UV irradiation testing, neutral salt spray testing, and outdoor exposure testing. To visually analyze the correlation between indoor and outdoor coating failure be-

haviors, B-spline smoothing curves for gloss loss, adhesion, and low-frequency impedance modulus were plotted using Origin 2021 software.

Figure 12 shows the B-spline curve changes for indoor and outdoor aging failure behavior of the polyurethane–acrylic coating. It is clearly visible that the gloss loss, adhesion, and low-frequency impedance modulus values from the multifactor cyclic accelerated test are closer to those from the outdoor exposure test. The neutral salt spray test shows intermediate values, while the single UV irradiation test yields the poorest correlation.

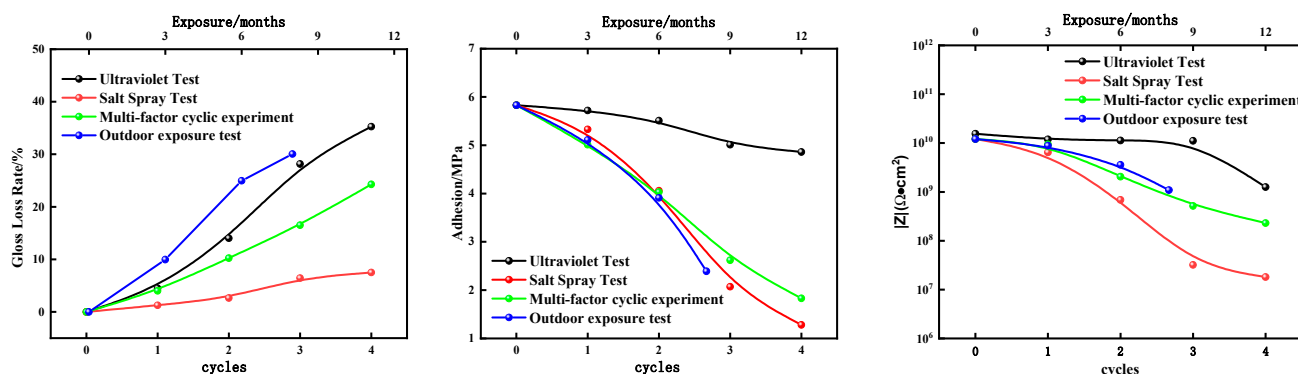


Figure 12. Changes in gloss loss, adhesion, and low-frequency impedance modulus of polyurethane–acrylic coatings in indoor and outdoor tests.

Table 2 indicates that the polyurethane–acrylic coating exhibits high correlation coefficients (corrcoef) of 0.9764, 0.9988, and 0.9929 for gloss loss, adhesion, and low-frequency impedance modulus, respectively, under the multifactor cyclic accelerated test compared to outdoor exposure testing. These values are also higher than the correlations observed in the other two tests, demonstrating the strong correlation between the multifactor cyclic accelerated test and outdoor exposure testing.

3.3.2. Quantitative Correlation Using Curve Fitting and Gray Relational Analysis

To quantitatively analyze the correlation between single UV irradiation tests, neutral salt spray tests, and multi-factor cyclic accelerated tests with outdoor exposure tests, the corrcoef function in MATLAB 2025 software can be used to calculate the correlation between the three indoor tests and outdoor exposure tests based on three aspects: loss of gloss, adhesion, and low-frequency impedance film values.

Table 2. The correlation coefficients of aging failure behaviors in indoor and outdoor tests of two coating chambers.

	Light Loss Rate	Adhesion	Low-Frequency Impedance Value
Single UV	0.9378	0.9837	0.8570
Neutral salt spray	0.9026	0.9944	0.9773
Multi-factor cycle	0.9764	0.9988	0.9929

Based on the specific processing steps for gray correlation [34,36] described above, the correlation coefficients for light loss rate, adhesion, and low-frequency impedance modulus were calculated between the three indoor tests and the outdoor exposure test. This analysis then examined the relationship between coating aging failure in the three indoor tests and coating aging in the outdoor exposure test.

The gray correlation coefficients for the indoor and outdoor failure behaviors of the polyurethane–acrylic/Q345B steel system are shown in Table 3. As indicated in the table,

the gray correlation coefficients between the indoor accelerated environment test results (light loss rate, adhesion, and low-frequency impedance film value) and the outdoor exposure test results for the polyurethane–acrylic coating are 0.8334, 0.8467, and 0.7977, respectively. Under single UV irradiation testing, the gray correlation coefficients were 0.7639, 0.4878, and 0.4637, and 0.6635, 0.8790, 0.6754 in neutral salt spray testing. This indicates that the correlation patterns between indoor and outdoor tests derived from gray correlation analysis are consistent with those obtained from curve fitting analysis.

Table 3. Gray correlation between aging failure behaviors of two coatings in indoor and outdoor tests.

	Light Loss Rate	Adhesion	Low-Frequency Impedance Value
Single UV	0.7639	0.4878	0.4637
Neutral Salt Spray	0.6685	0.8790	0.6754
Multi-factor cycle	0.8334	0.8467	0.7977

For the polyurethane–acrylic/Q345B steel system, the gray correlation coefficients between single UV irradiation or neutral salt spray tests and outdoor exposure tests were lower than those between multi-factor cyclic accelerated tests and outdoor exposure tests. This indicates that multi-factor cyclic accelerated testing better simulates the aging failure behavior of the polyurethane–acrylic/Q345B steel system under the atmospheric conditions of Wenchang.

3.3.3. Mechanisms of Coating Failure in Hainan’s Coastal Atmospheric Environment

Figure 13 shows SEM images of polyurethane–acrylic coatings after varying durations of outdoor exposure. Prior to outdoor exposure, the coating surfaces exhibited overall smoothness and flatness with no apparent defects. After 8 months of outdoor exposure, slight increases in surface roughness and localized micro-blistering became observable. Elemental analysis of the blistered areas revealed, based on the elemental distribution in Figure 13, that the Na content in these regions was 1.16% and the Cl content was 1.04%. This indicates that corrosive media such as water molecules and chloride ions had penetrated to the organic coating/metal interface, confirming that the blistering was caused by the penetration of corrosive media to the metal interface.

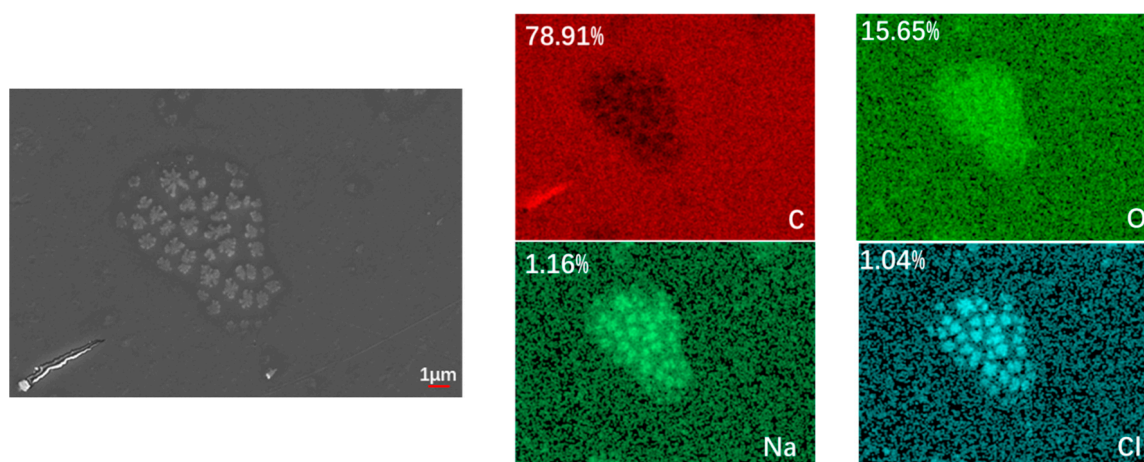


Figure 13. SEM microstructure and EDS elemental distribution of polyurethane–acrylic coating after 8 months of outdoor exposure.

Based on the combined results of SEM and EDS analysis, along with other apparent aging behavior assessments, polyurethane–acrylic coatings exhibited significant failure when exposed outdoors, though their failure mechanisms differed.

The aging failure of the polyurethane–acrylic coating progresses through three distinct stages. During the initial failure phase, corrosive media continuously migrate into the coating through minute defects. In the intermediate failure stage, prolonged outdoor exposure to sunlight irradiation, water, ions, and oxygen causes polymer chain and bond breakage. This increases micro-defects within the organic coating, forming mass transfer pathways that facilitate the penetration of corrosive media toward the organic coating/metal interface. Upon reaching the organic coating/metal interface, corrosive media exhibit mutual attraction, aggregating and accumulating at this boundary. This creates osmotic pressure, further facilitating the migration of water molecules from the external environment through the coating into the solution zone. As the solution zone expands, osmotic pressure continuously increases. Research indicates that when expansion pressure reaches 2–3 MPa, it disrupts the bond between the coating and the metal substrate. If expansion pressure continues to increase beyond the coating's pressure resistance (i.e., the sum of coating adhesion and coating strength), the coating deforms and blisters. In the later stages of failure, electrochemical corrosion reactions occur on the metal substrate, generating corrosion products. These products accumulate, causing the coating blisters to enlarge.

4. Conclusions

To investigate the effects of various environmental factors in marine atmospheric conditions on coating/Q345B steel systems, a multi-factor cyclic accelerated test was designed. Outdoor exposure tests in Wenchang, Hainan, single UV irradiation aging tests, neutral salt spray tests, and multi-factor cyclic accelerated tests were conducted. The changes in apparent morphology, gloss, gloss loss rate, adhesion, and electrochemical behavior during testing were analyzed for two coating systems (epoxy resin/Q345B steel system and polyurethane–acrylic/Q345B steel system) were analyzed for changes in apparent morphology, gloss and gloss loss rate, adhesion, and electrochemical behavior during the test process. The results are as follows:

Tracking the failure behavior of the polyurethane–acrylic coating system in the outdoor atmosphere of Wenchang, Hainan: As the outdoor exposure test progressed, the polyurethane–acrylic coating was significantly affected by the penetration of corrosive media. These media penetrated the interface, accumulated, caused blistering, and generated corrosion products. The coating's surface gloss was minimally affected, and its adhesion remained strong, with a loss rate reaching 59%. The electrochemical low-frequency impedance decreased to $10^9 \Omega \cdot \text{cm}^2$, indicating a relatively high impedance despite the presence of rust spots beneath the coating film.

The failure behavior of the polyurethane–acrylic coating under single test conditions revealed that corrosive media penetration is the dominant factor governing adhesion loss and electrochemical degradation, whereas UV irradiation plays a more pronounced role in gloss reduction. Simultaneously, curve fitting analysis and gray correlation analysis reveal that the correlation between multi-factor cyclic accelerated tests and outdoor exposure tests is higher than that of single ultraviolet irradiation aging tests and neutral salt spray tests, demonstrating the feasibility of multi-factor cyclic accelerated testing.

Although the proposed multi-factor cyclic accelerated test showed strong correlation with outdoor exposure results, several limitations should be acknowledged. First, the present study focused on a simplified single-layer polyurethane acrylate clear varnish system in order to facilitate direct observation of degradation evolution and interfacial failure behavior. Such a model coating system does not fully represent practical heavy-

duty protective coating systems containing anticorrosive pigments, fillers, or multilayer barrier structures. Therefore, the conclusions obtained in this work are mainly applicable to degradation mechanism analysis and accelerated test methodology development.

Future work will focus on extending the indoor–outdoor correlation analysis to practical multilayer protective coating systems, including epoxy/polyurethane composite coatings and zinc-rich anticorrosive systems. Additional studies involving longer exposure durations, multiple climatic regions, and statistical uncertainty analysis will also be carried out to further improve the universality and predictive capability of the accelerated testing methodology.

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