coatings

Article

Evaluation of Anticorrosion Coatings for Offshore Wind Turbine Monopiles for an Optimized and Time-Efficient Coating Application

Nevena Marinova [1],*[iD], Aiala Urbegain [1], Pablo Benguria [1][iD], Andreu Travé [2] and Raúl Caracena [1],*

1 Tecnalia, Basque Research and Technology Alliance (BRTA), Parque Tecnológico de San Sebastián Mikeletegi Pasealekua, 2, 20009 San Sebastián, Spain; aiala.urbegain@tecnalia.com (A.U.); pablo.benguria@tecnalia.com (P.B.)
2 Travé Consulting, Avda Rius I Taulet 125 G, 08173 Sant Cugat del Vallés, Spain; traveandreu@gmail.com
* Correspondence: nevenamarinova@abv.bg (N.M.); raul.caracena@tecnalia.com (R.C.)

Abstract: Offshore corrosion is a critical issue for metallic offshore structures. In this study, we investigated the corrosion protection of 12 coating systems for offshore monopiles in atmospheric, splash, and submerged zones, and we compared their performance under accelerated laboratory testing according to ISO 12944 with real field exposure. The results showed that the aging of the coatings did not accelerate at the same rate in all coatings. Furthermore, we observed that for some types of laboratory tests, the results are not representative of real field exposure as the laboratory test is much less aggressive than the real offshore conditions. This observation confirms that the field exposure data provide valuable information in order to properly assess the corrosion protection of coatings and thus the expected lifetime of the offshore structure. Additionally, we analyzed the rate-determining steps involved in the application of the coating onto the entire monopile and quantified the possibility of achieving a more time efficient coating process. Our results contribute to a better understanding of the issues related to testing and qualification of corrosion protection coatings for offshore structures and provide useful insights for the selection of coating solutions at the industrial level.

Keywords: offshore coatings; corrosion protection; monopile; corrosion testing; ISO 12944

1. Introduction

Corrosion is a critical phenomenon to be considered in the design, construction, commissioning, and operation lifetime of offshore structures such as offshore wind generators. Since these installations usually operate at remote locations with difficult access, revision and maintenance are complicated, and repair in the case of failure is challenging. For this reason, the selection of a corrosion protection system for offshore wind generators is a key process that can have a very serious effect on the future lifetime and maintenance of the structure [1]. The standard DNV-OS-J101 [1] describes the design bases and the corrosion protection of offshore wind generators. A key parameter to consider in the corrosion protection design is the specifics of the local environment. ISO 12944:9 [2] and ISO 12944:2 [3] define three specific environments to which the metallic offshore structure is exposed: atmospheric zone, splash zone, and submerged zone (Table 1, Figure 1).

Table 1. Corrosion zones defined in ISO 12944.

ISO 12944-9:2018	Corrosivity Category	Durability	Environment
Atmospheric	CX		
Splash	CX / Im4	15–25 years	Marine offshore
Immersion	Im4		

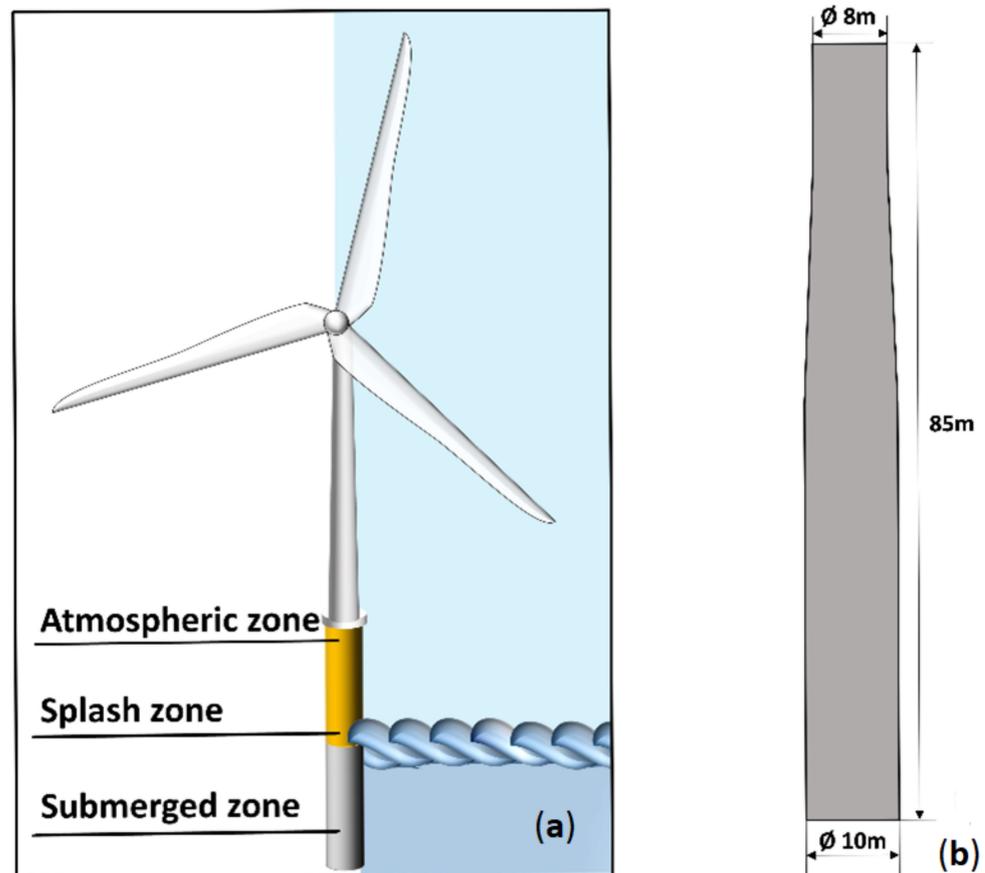**Figure 1.** (**a**) Corrosion zones in an offshore wind generator. (**b**) Schematics and dimensions of the monopile considered in the study.

The atmospheric zone is where the external and internal surfaces of the steel structures are exposed to the offshore atmosphere without direct contact with seawater. This zone should be protected by a coating.

The splash zone is the part of the structure that is intermittently exposed to seawater due to the action of tide or waves or both. As a consequence, the corrosive environment is severe, maintenance of corrosion protection is not practical, and cathodic protection is not effective in this zone.

The submerged zone consists of the region below the lower limit of the splash zone. External surfaces of the submerged zone should have cathodic protection (CP). Use of a coating is optional and is primarily intended to reduce the required CP capacity. The coating system applied for this zone should have a documented compatibility with CP [1].

It can be summarized that the use of a coating is mandatory in the atmospheric and splash zones while in the submerged zone, it is optional and primarily intended to reduce the required cathodic protection [4].

The protective coating applied to the different parts of an offshore wind power structure is designed for the specific environmental conditions of each zone of exposure. Thus, for the atmospheric zone, the effect of salt spray, wetting, fluctuation in the temperature, and effect of UV light should be considered. In contrast, the submerged zone is always fully immersed in seawater with a limited effect of UV light, but the negative voltage applied due to the cathodic protection should be considered. The splash zone is exposed to the combined effect of the external force, temperature fluctuation, intermittent wetting, and seawater immersion [5]. To ensure that the protective coating can provide the necessary protection during the expected lifetime of the structure, qualification tests designed for each zone are defined in ISO 12944-9 [2] The latter standard specifies the performance

requirements for protective paint systems for offshore and related structures. Table 2 shows the required prequalification tests for each zone as defined in ISO 12944-9.

Table 2. Qualification tests for offshore coatings for different corrosivity categories.

Test	CX (Atmospheric Offshore)	CX (Offshore) + Im4 (Splash and Tidal Zones)	Im4 (Submerged Zone)
Cyclic test annex B of ISO 12944-9	4200 h	4200 h	-
Cathodic disbonding ISO 15711, method A	-	4200 h	4200 h
Seawater immersion, ISO 2812-2	-	4200 h	4200 h

Accelerated testing used for qualification has the advantage of quickly providing results in predefined conditions [6]. However, the qualification of the system does not guarantee successful corrosion protection since many other factors are decisive for the durability of the system [4]. The accelerated testing is carried out under ideal laboratory conditions onto optimally coated test coupons, which often differs from real life situation [7,8]. Field exposure data, when such are available, could be a very useful supplement that verifies the accelerated laboratory testing results [6,9,10].

One of the most common type of offshore wind turbine foundation is the monopile, which is a tubular metallic structure that supports the whole wind turbine and fixes it at the seabed. Some of the largest monopiles can reach a longitude of 85 m and a diameter of 10 m (Figure 1b) and have a surface area to be coated of close to 2000 m^2.

The main goal of this study was to investigate the corrosion behavior of the 12 selected protective coating systems for offshore monopiles by performing accelerated laboratory qualification tests and comparing the results of the testing with those of field exposure.

Additionally, the study analyzed the time factor in the application of the coating in the painting booth. Since applying a coating on a large area structure such as a monopile is a costly and long process, avoiding time-consuming operations could significantly improve the productivity. One bottle neck in the whole monopile fabrication process is the application of the coating in a coating booth. Reducing the time that the monopile spends in the coating booth would result in improved efficiency in monopile production. This study explores the possibility of the optimization of the coating booth operations, in order to reduce the time required for the coating application and quantifies the effect of the temperature in the coating booth as a tool for the optimization of the coating process.

2. Materials and Methods

2.1. Nomenclature of the Analyzed Coatings

For this study, four of the leading coating manufacturers were contacted and asked to provide their coating solutions for an offshore monopile. The term "coating solution" refers to a complete set of three coating systems, one for each zone of exposure provided by the same manufacturer. We studied four coating solutions in this paper, which are referred to as Solution 1, Solution 2, Solution 3, and Solution 4 from four different coating manufacturers. Each coating solution contained three coating systems, one for each zone of exposure (atmospheric, splash, and submerged). The coating systems are referred as A for atmospheric, S for splash zone, and I for the submerged zone (from immersion), followed by the number of the coating solution that they belong to and some indication of the chemical compositions. Each coating system was composed of two or three coating layers: all coating systems contained a primer and topcoat; some of them also contained an intermediate layer. The coating layers within a coating system and the required thickness of each layer have been defined by the coating manufacturer and are described in Tables 3–5.

Table 3. Environmental conditions at the HarshLab testing facility.

Parameter	Value
Annual precipitation	1500 mm/year
Mean interannual temperature	Min 13 °C, Max 16 °C
Average interannual temperature	Min 10 °C, Max 16 °C
Average insolation	1825 h/year
Average annual wetting time (RH * > 80%, T > 0 °C)	5960 h
Water temperature	Min 11 °C (January), Max 22 °C (August)
Significant wave height	Min 1.15 m, Max 9.62 m, Average 1.67 m
Average salinity:	35 USP.
Average dissolved O_2	6 mL/L
Average transmittance:	88%

* RH stands for relative humidity.

Table 4. Selected coating systems for the atmospheric zone.

Atmospheric Zone			
Reference	Chemical Composition and Thickness	NDFT * (μm)	DFT Measured (μm)
A1-Zn **	Zinc rich epoxy 60 μm Epoxy 160 μm Polyurethane (yellow) 60 μm	280	281
A2-Epox ***	Epoxy 200 μm Epoxy 200 μm Polyurethane (white) 60 μm	460	485
A3-Zn	Zinc rich epoxy 60 μm Epoxy 160 μm Polyurethane (yellow) 60 μm	280	399
A4-Zn	Zinc rich epoxy 60 μm Epoxy 170 μm Polyurethane (grey) 50 μm	280	312

* NDFT—net dry film thickness as provided by the manufacturer; ** Zn—zinc-rich; *** Epox—epoxy based composition.

Table 5. Selected coating systems for the splash zone.

Splash Zone			
Reference	Chemical Composition and Thickness	NDFT (μm)	DFT Measured (μm)
S1	Epoxy 275 μm Epoxy 275 μm Polyurethane (yellow) 60 μm	610	691
S2-GF	Epoxy GF * 300 μm Epoxy (grey) GF 300 μm	600	728
S3-GF	Epoxy GF 300 μm Epoxy GF 300 μm Polyurethane (yellow) 60 μm	660	821
S4	Epoxy 300 μm Epoxy (grey) 300 μm	600	629

* GF—glass flakes.

2.2. Preparation of the Test Coupons

The application of the coating was carried out by the manufacturer according to the corresponding coating protocol. The coatings were applied onto standard carbon steel coupons with dimensions of 150 × 75 × 3–5 mm. The surface of the coupons was prepared according to ISO 8503-1 grade Sa $2\frac{1}{2}$, roughness grade G. The coatings from Solutions 1, 2,

and 3 were applied by airless spray, and coating 4 by airbrush. A scribe line as described in ISO 12944:9 was produced on the test panels for some of the tests in order to ensure full exposure of all the elements to the test environment. For each test, three coupons were prepared and tested, and the data presented in the Results section are the average of the three coupons. Photographs of the testing coupons before and after aging are shown in the Supplementary Materials (SM).

2.3. Accelerated Laboratory Aging

Table 2 shows the laboratory methods used for the accelerated aging of the coating systems.

2.3.1. Atmospheric Zone

The coatings for the atmospheric zone were aged by a cyclic test as defined by ISO 12944:9. The cyclic test includes 25 cycles with a total duration of 4200 h. The aging cycle has a duration of 168 h and includes the following steps:

- 72 h of exposure to UV and condensation;
- 72 h of exposure to neutral salt spray; and
- 24 h of exposure to low temperature at (-20 ± 2 °C).

2.3.2. Splash Zone

The coatings for the splash zone were aged using three different methods:

1. The cyclic test, which also applies for the atmospheric zone coating cyclic method.
2. Seawater immersion test as defined in ISO 2812-2 [11], In this test, the coated panels are immersed in synthetic seawater for 4200 h at 40 °C. The panels are placed on a support that keeps them at an angle of 15 to 20° to the vertical. During aging, the aeration is ensured by constant circulation of the seawater.
3. Cathodic disbonding according to ISO 15711 [12]. In this test, the cathodic protection of the offshore structure is simulated in artificial seawater and the resistivity of the coating to disbonding is evaluated. To initiate the cathodic disbonding, a 6 mm diameter circular holiday is created in the coating in order to expose the steel substrate to the environment. Then, the panel is connected to the cathodic protection circuit and placed in artificial seawater for 4200 h. The test system is under constant steering to ensure aeration.

2.3.3. Submerged Zone

1. Seawater immersion test as defined in ISO 2812-2; and
2. Cathodic disbonding according to ISO 15711.

2.4. Field Exposure Conditions

In parallel to the laboratory testing, the corrosion resistance of the coating to offshore conditions were also assessed by exposing the coating systems to a real offshore environment in the floating platform-laboratory HarshLab [11], located at Biscay Bay. The platform is moored in the Cantabrian Sea in the BiMEP area [12], 2.2. km away from the coast. HarshLab is a unique offshore infrastructure designed for testing new materials and solutions against corrosion, aging and fouling in immersion, splash, and atmospheric zones (Figure 2). The environmental conditions of the test site are listed in Table 3. The test panels were exposed at the HarshLab facility for a period of one year.
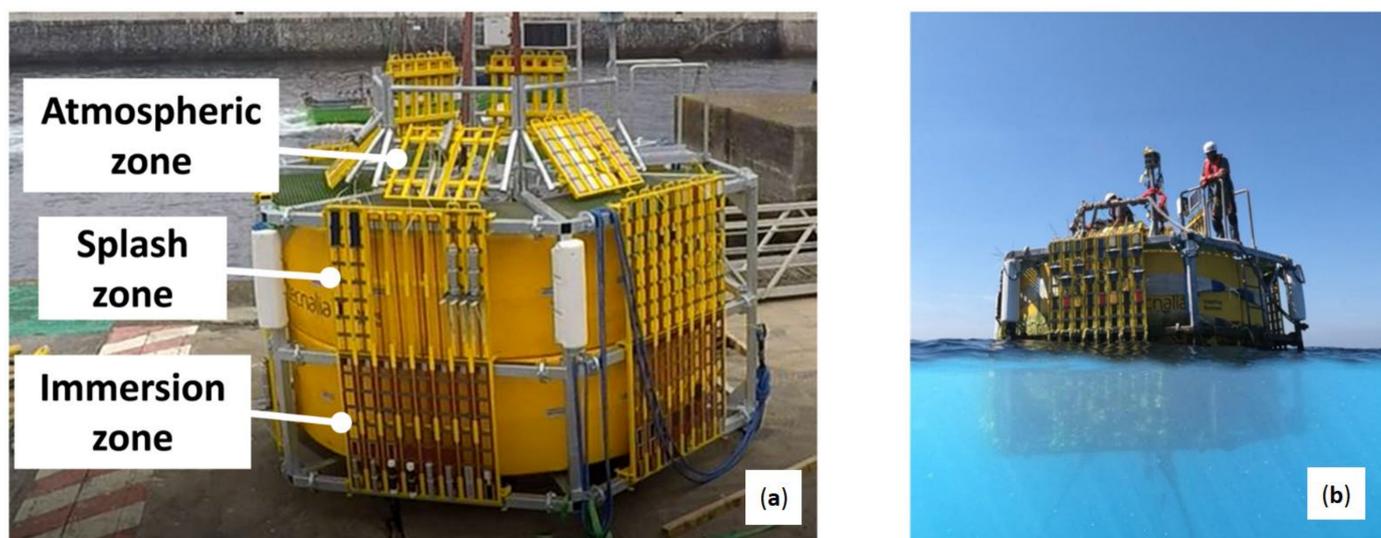
Figure 2. (**a**) The HarshLab 1.0 facility prior to commissioning, prepared to accommodate test panels for field exposure in the atmospheric, splash, and immersion zones. (**b**) The HarshLab moored in the Cantabrian Sea.

2.5. Coating Characterization and Assessment

The coating thickness and chemical composition of the studied coatings are listed in Tables 4–6.

Table 6. Selected coating systems for the submerged zone.

Submerged Zone (Immersion)			
Reference	**Chemical Composition and Thickness**	**NDFT * (μm)**	**DFT Measured (μm)**
I1	Epoxy 50 μm Epoxy (yellow) 300 μm	350	440
I2-GF	Epoxy GF 200 μm Epoxy (grey) GF 200 μm	400	435
I3	Epoxy 200 μm Epoxy (grey) 150 μm	350	461
I4 *	Epoxy 300 μm Epoxy (grey) 300 μm	600	629

* System I4 is the same coating system as S4.

- Thickness measurement: the total dry film thickness (DFT measured) was measured by magnetic induction in accordance with ISO 2178 [13] using a FISCHER thickness gauge, model DUALSCOPE MP0R (FISCHER, Waltham, MA, USA).
- Adhesion: the pull adhesion test was carried out on new and aged panels according to the ISO 4624 [14]. Ø20 mm dollies were attached to the coating panel using epoxy adhesive. The adhesion strength was measured with a DEFELSKO adhesion device model POSITEST AT (DEFELSKO, New York, NY, USA). Three samples were measured for each system, and three different zones were tested in each panel. The fracture mode was evaluated according to ISO 4624 as interface (adhesive) failures, which are indicated as A/B, B/C, C/D, D/Y, and Y/E, where A is the metallic substrate, B, C, and D are the different layers of the coating systems, Y is the glue used to attach the dolly, and Z is the dolly (Figure 3). Cohesive failures within one layer are indicated by the corresponding layer letter indicator.
- Corrosion penetration at scribe (creep) was evaluated according to ISO 12944-6 [15].
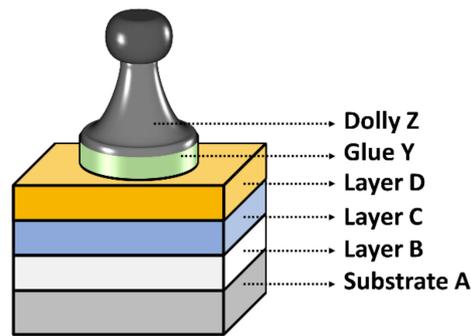
Figure 3. Schematics of the coated substrate and their designation in the analysis of the fracture mode.

3. Results and Discussion

3.1. Atmospheric Zone

The adhesion pull-off strength of a coating system is an important parameter that indicates how efficient the coating is attached to the substrate surface. The pull-off adhesion strength of the atmospheric coating systems are shown in Table 7 and Figure 4a.

Table 7. Adhesion strength (average) of coating systems for atmospheric zone before and after aging and field exposure.

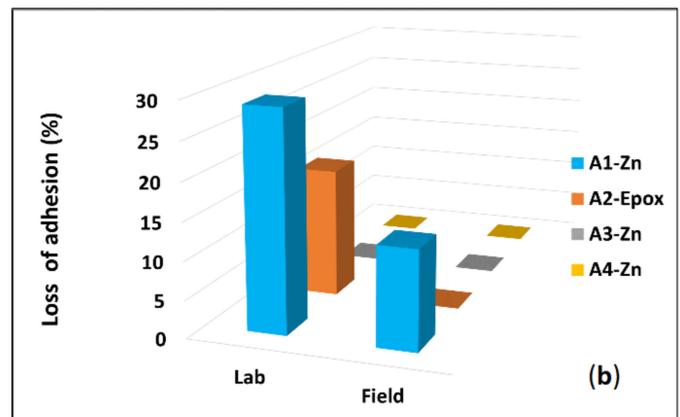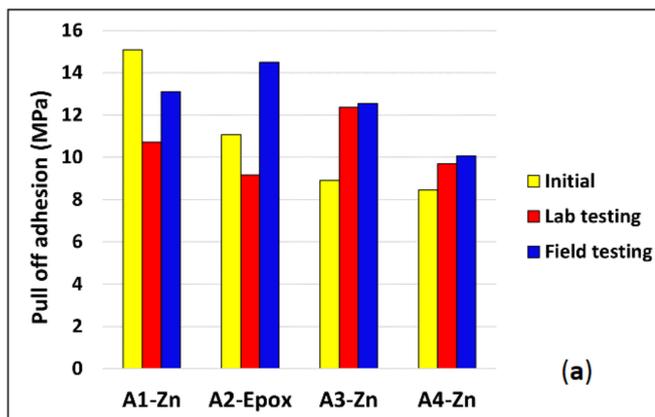| Ref.	Initial		Cycling Aging (4200 h)		Field Exposure (1 Year)	
	Fracture Mode	Adhesion (MPa)	Fracture Mode	Adhesion (MPa)	Fracture Mode	Adhesion (MPa)
A1-Zn	100% D	15.09	70% A/B, 30% D	10.72	100% D	13.12
A2-Epox	55% C/D 45% C,	11.06	100% C	9.17	85% C, 15% C/D	14.50
A3-Zn	80% D, 20% C	8.90	70% D, 20% C, 10% C/D	12.38	70% D, 20% C, 10% B	12.54
A4-Zn	95% B, 10% B/C	8.45	100% C	9.70	50% C, 50% B	10.07

Figure 4. (**a**) Pull-off adhesion strength of the coatings for the atmospheric zone before and after aging and field exposure. (**b**) Loss of adhesion of the coating systems after aging and field exposure.

The initial average adhesion strength was in the range 8.45–15.09 MPa, which is well above the minimum pull-off strength value of 5 MPa as stated in ISO 12944-9. None of the systems exhibited adhesive fracture mode A/B type. The A/B type of failure suggests adhesion problems at the metallic substrate/primer coating interface. A4-Zn showed a predominantly cohesive fracture of the B undercoat layer, but the substrate remained protected. All systems complied with the acceptance criteria defined in 12944-9. After the accelerated aging, in some cases, the pull-off strength was slightly decreased but still above the limiting value. The fracture mode of system A1-Zn changed to A/B, which is a serious indication of possible weakness in the corrosion protection of the system;

however, the pull-off strength remained far above the limiting value of 5 MPa. In the case of systems A3-Zn and A4-Zn, the pull-off strength was increased in both the laboratory aging and field exposure. This phenomenon might be due to post-curing of the polyurethane coatings during the aging, which is mainly caused by UV light. This effect was even more pronounced after the field exposure of the coating and in three of the four systems, the pull-off strength increased and no loss of adhesion was observed (Figure 4b).

For systems A2-Zn and A2-Epox, the accelerated aging caused more severe degradation of the pull-off strength than the one-year field exposure. However, for field exposure, there were no acceptance criteria to be applied.

Another very important parameter is the corrosion penetration under the scribe. The scribe artificially introduces defects of the coating, which accelerates the corrosion by exposing the uncoated metallic substrate and all components of the coating system to the corrosive environment. The scribe creep evaluation followed the guidelines of ISO 12944-6. Figure 5a shows the corrosion penetration under the scribe in mm. In three of the four systems, the penetration of the corrosion was significantly higher after accelerated aging than field exposure. This result could be expected since the qualification tests aimed to ensure corrosion protection for a period of at least 15 years in real offshore conditions while the field exposure in this study was one year. Two of the systems (A1-Zn and A2-Epox) showed corrosion penetration higher than 3.0 mm in the qualification test, which is the limiting value for the offshore CX category, as stated by 12944-9. This suggests that only systems A3-Zn and A4-Zn comply with the standard.
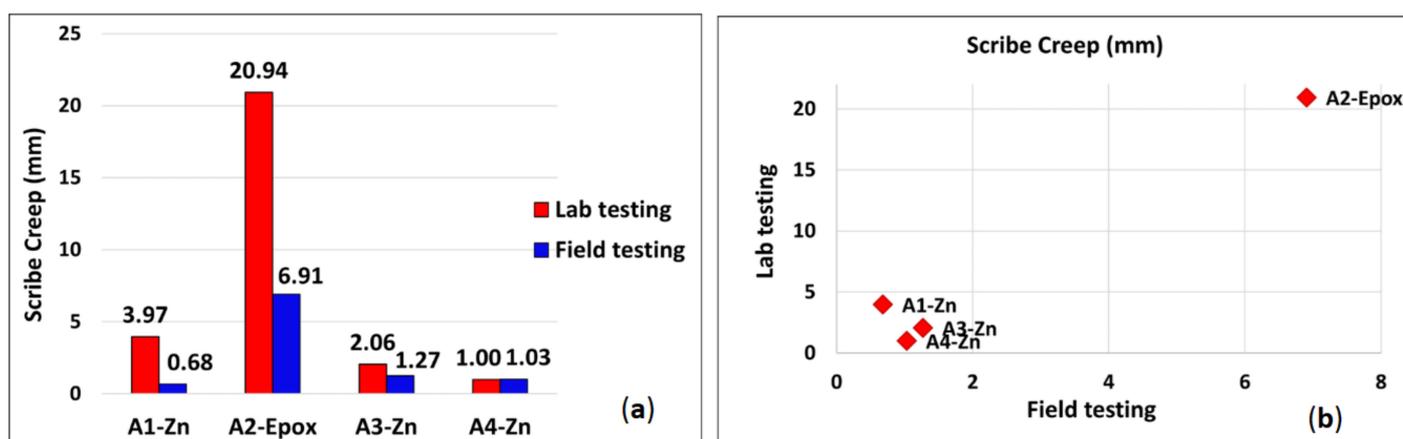

Figure 5. (**a**) Scribe creep of the atmospheric zone coating systems after accelerated aging and field testing. (**b**) Scribe creep after accelerated aging plotted as a function of scribe creep after field exposure.

As can be seen in Figure 5b, the correlation between the results of scribe creep obtained from laboratory aging and field exposure showed a rather poor correlation. However, the behavior of A2-Epox was consistent and this coating system was the worst performing coating in both the accelerated aging and field testing. This result was expected and is due to the merely organic nature of A2-Epox and the lack of Zn-rich primer, which is essential for the anticorrosion protection of the coating.

3.2. Splash Zone

The prequalification of the coating systems for the splash zone includes three types of laboratory aging: cyclic aging, immersion aging, and cathodic disbonding. Table 8 and Figure 6 show the pull-off adhesion strength of the coatings before and after laboratory aging (cyclic and immersion) and after one year of field exposure. The initial adhesion strength was in the range 7.75–16.25 MPa, which complies with the requirement stated in ISO 12944-9. The worse performing systems were S2-GF and S3-GF. These systems contain

GF in their composition, which is rather surprising since GF containing coatings usually have improved resistance.

Table 8. Adhesion strength (average) of the coating systems for the splash zone before and after aging and field exposure.

| Ref.	Initial		Cycling Aging (4200 h)		Immersion Aging (4200 h)		Field Exposure (1 Year)	
	Fracture Mode	Adhesion (MPa)	Fracture Mode	Adhesion (MPa)	Fracture Mode	Adhesion (MPa)	Fracture Mode	Adhesion (MPa)
S1	100% D	13.81	100% D	14.56	55% D/Y, 45% D	15.51	100% D	14.69
S2-GF	100% C	10.20	81%C, 19% B	7.34	100% B	8.77	50% B, 50% C	9.67
S3-GF	90% D, 10% C/DC	7.75	90% D, 10% C/D	11.71	47% C/D, 46% D, 7% D/Y	12.11	60% D, 40% C/D	11.13
S4	45% B, 40% C, 5%C/Y	16.52	90% C, 10% B/C	14.20	91% C, 9% B/C	17.08	90% C, 10% B/C	10.41
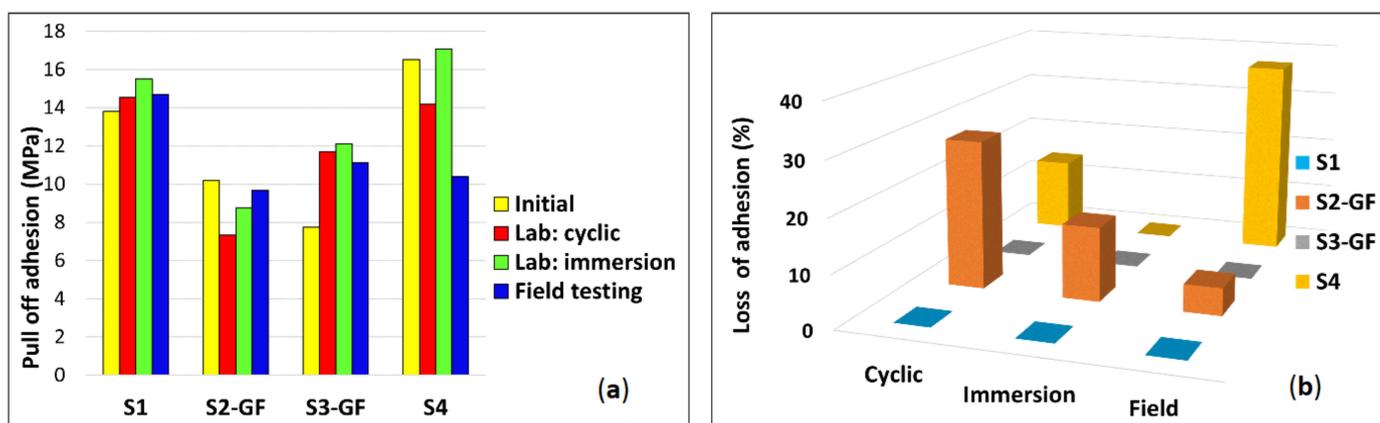
Figure 6. (**a**) Pull-off adhesion strength of the coatings for splash zone before and after laboratory aging and field exposure. (**b**) Loss of adhesion of the coating systems after aging and field exposure.

After the accelerated aging, all coating systems exhibited pull-off adhesion strength above the required 5 MPa and the critical A/B failure mode was observed in none of the cases. System S2 showed a close to 30% loss of adhesion after cyclic aging and close to 15% after immersion aging, but still complied with the standard. On the other hand, S4 showed a significant loss of adhesion after field exposure, which was rather unexpected. This result suggests that the real offshore conditions are more damaging for this coating system than the cyclic accelerated test and that this type of aging might not be representative for this particular coating system.

Figure 7 and Table 9 show the corrosion under the scribe for the splash zone coating system. Apparently, there was a huge difference in the aggressivity of the cycling and immersion aging. The corrosion penetration under the scribe after cyclic aging was in the range 12.79–16.90 mm, which was far above the acceptable penetration of 8 mm as defined in ISO 12944-9. This result means that none of the coatings can be qualified as suitable for this application. On the other hand, the corrosion creep after the immersion test was very low with the highest value of 0.3 mm, which is practically negligible when compared to the data from cycling aging. The results after field exposure were in-between the values of the two types of laboratory aging, but the difference between the immersion test and field exposure remained very significant, reaching a factor of 35 for the case of S3-GF. Furthermore, the highest corrosion penetration was recorded for systems S2-GF and S3-GF, which were also the systems with the highest DFT measured. Based on our previous experience with GF containing coatings, we speculate that the reason for the

higher corrosion penetration might be the fact that the GF additive in the coating has a specific mode of breakage, which leaves open channels in the coating layer. This makes the system more vulnerable to corrosion penetration since the channels allow the environment to easily penetrate the coating layer under the scribe. However, further investigation is required in order to clarify the exact reason.
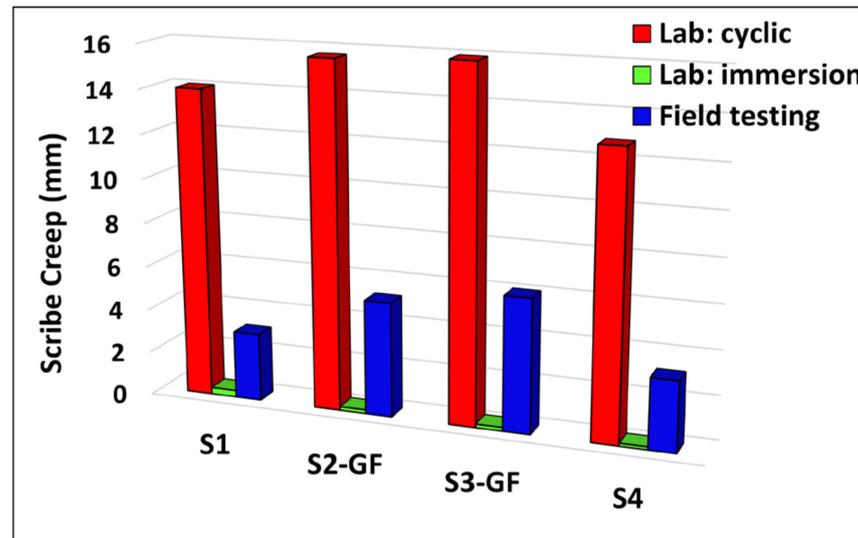

Figure 7. Scribe creep of the splash zone coating systems after accelerated aging and field testing.

Table 9. Scribe creep in mm for the splash zone coating system before and after laboratory aging and field exposure.

Ref.	Cyclic Aging (mm)	Immersion Aging (mm)	Field Exposure (mm)
S1	14.01	0.30	3.09
S2-GF	15.67	0.17	5.20
S3-GF	15.90	0.17	6.06
S4	12.79	0.13	3.19

The correlation of the values obtained after cyclic aging and field exposure (Figure 8a) showed that the behavior of the coatings was rather consistent in both the laboratory test and field exposure, and that comparative performance of the coating was similar. Figure 8b shows the data for the scribe creep after immersion aging plotted versus the data of field exposure, but in this case, is was difficult to see the trend since the values of creep after immersion aging were an order of magnitude lower than the one from field exposure and approached the error of the measurement.

The resistance of the coatings to cathodic protection is included in the SM since no relevant field testing was carried out so no comparison could be made.
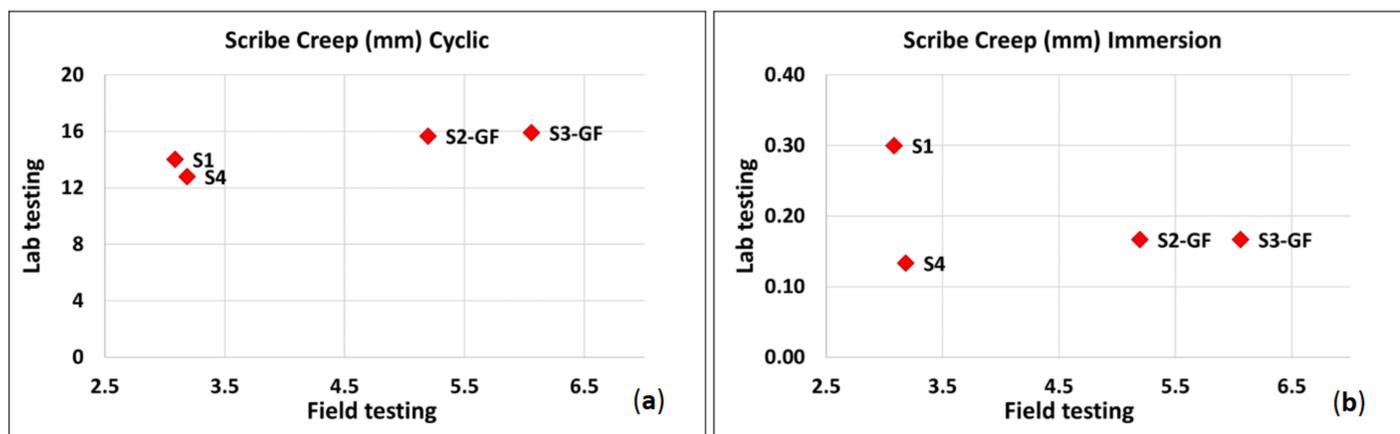
Figure 8. Scribe creep after accelerated aging, (**a**) cyclic, (**b**) immersion, plotted as a function of scribe creep after field exposure.

3.3. Immersion Zone

The pull-off adhesion strength of the coating systems for the submerged zone is shown in Table 10 and Figure 9. Systems I1 and I2-GF showed a decrease in adhesion strength after 4200 h of immersion, while I3 and I4 showed an improvement in the adhesion. The field results indicated a slight decrease in adhesion strength in system I3 and I4, and a very significant drop in system I1 (more than 55%, Figure 9b) while I2-GF showed a slight improvement. Interestingly, in several systems, a change in the fracture mode to the undesired A/B type was observed. However, the initial adhesion strength and the values after accelerated aging complied in the case of I1 with the standard, despite the A/B fracture mode.

Table 10. Adhesion strength (average) of the coating systems for the submerged zone before and after aging and field exposure.

Ref.	Initial		Immersion Aging (4200 h)		Field Exposure (1 Year)	
	Fracture Mode	Adhesion (MPa)	Fracture Mode	Adhesion (MPa)	Fracture Mode	Adhesion (MPa)
I1	65% C, 35% C/Y	13.02	45% A/B, 35% C/Y, 20% C	11.83	65% A/B, 35 C	5.77
I2-GF	100% C	10.09	85% C, 15% C/Y	9.15	50% B, 25% C, 25% B/C	11.50
I3	86% B, 14% C	12.01	73% B, 27%C	14.30	50% B, 50% C	11.07
I4	45% B, 40% C, 5% C/Y	16.52	38% B, 35% C/Y, 7% B/C, 7% Y/Z, 7% Y	17.08	55% B, 35% C, 10% B/C	13.94

The scribe creep after immersion aging and field exposure is shown in Figure 10. As can be seen, the accelerated immersion aging produced very limited corrosion scribe penetration, therefore all systems complied with the standard, which sets the limiting value of 6 mm. These results reproduce the results from the immersion test of the splash zone systems. However, when analyzing the results recorded after field exposure, we observed several times higher creep penetration, and, in some cases, as in the case of system I1, more than seven times higher. These results suggest that the accelerated immersion aging does not seem to be representative for the coating systems in this study. The correlation of the laboratory and field performance (Figure 10b) is not straightforward, but the worst performing system in laboratory also showed the worst results in field. The scribe creep penetration in the qualification tests remained far below the limiting value of 6 mm systems, as stated by the standard for all coatings, which suggests that the coating complied with the latter.
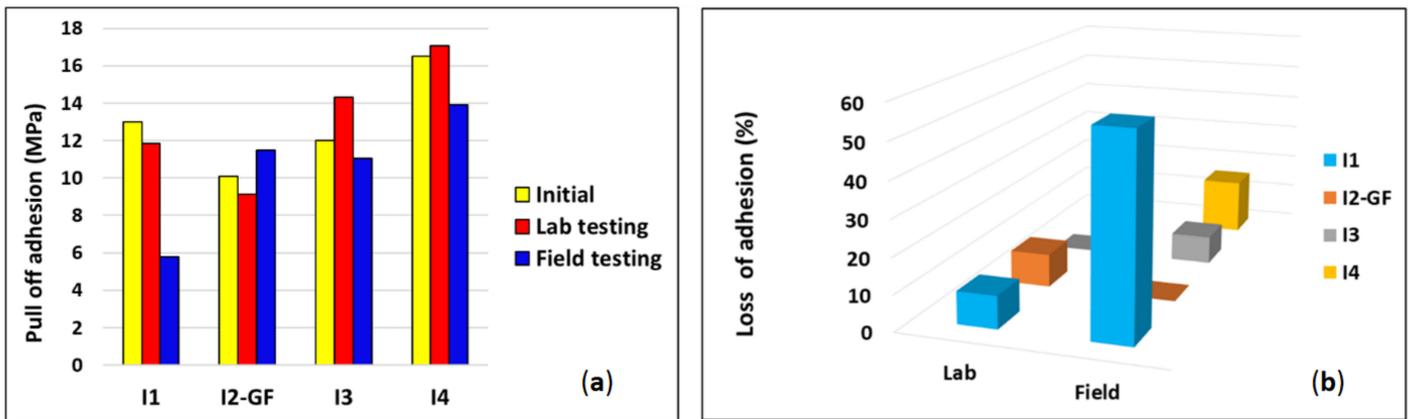
Figure 9. (**a**) Pull-off adhesion strength of the coatings for the submerged zone before and after laboratory aging and field exposure. (**b**) Loss of adhesion of the coating systems after aging and field exposure.
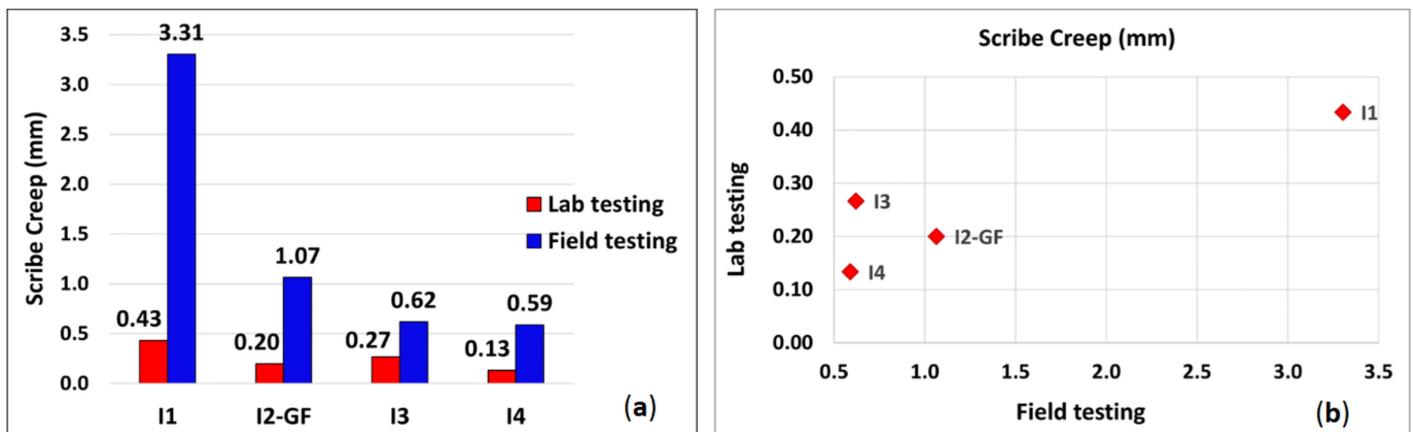

Figure 10. (**a**) Scribe creep of the submerged zone coating systems after accelerated aging and field testing. (**b**) Scribe creep after accelerated aging plotted as a function of scribe creep after field exposure.

The scribe creep after immersion aging and field exposure is shown in Figure 10. As can be seen, the accelerated immersion aging produced very limited corrosion scribe penetration, therefore all systems complied with the standard, which sets the limiting value of 6 mm. These results reproduced the results from the immersion test of the splash zone systems. However, when analyzing the results recorded after field exposure, we observed several times higher creep penetration and, in some cases, as in the case of system I1, more than seven times higher. These results suggest that the accelerated immersion aging does not seem to be representative for the coating systems in this study. The correlation of the laboratory and field performance (Figure 10b) is not straightforward, but the worst performing system in laboratory also showed the worst results in the field. The scribe creep penetration in the qualification tests remained far below the limiting value of 6 mm systems, as stated by the standard for all coatings, which suggests that the coatings complied with the latter.

The resistance of the coatings to cathodic protection was included in the SM since no relevant field testing was carried out and no comparison could be made.

3.4. Acceleration Factor

In order to compare the field and laboratory test data, the acceleration factor *A* using the average value of the scribe creep was calculated according to Equation (1) [10].

$$A = \frac{x_{test}}{x_{field}} \times \frac{t_{field}}{t_{test}} \tag{1}$$

where x_{test} and x_{field} are the scribe creep penetration measured after the accelerated tests and field exposure, respectively; t_{test} = 175 days; and t_{field} = 365 days. The results for A are shown in Table 11 and Figure 11.
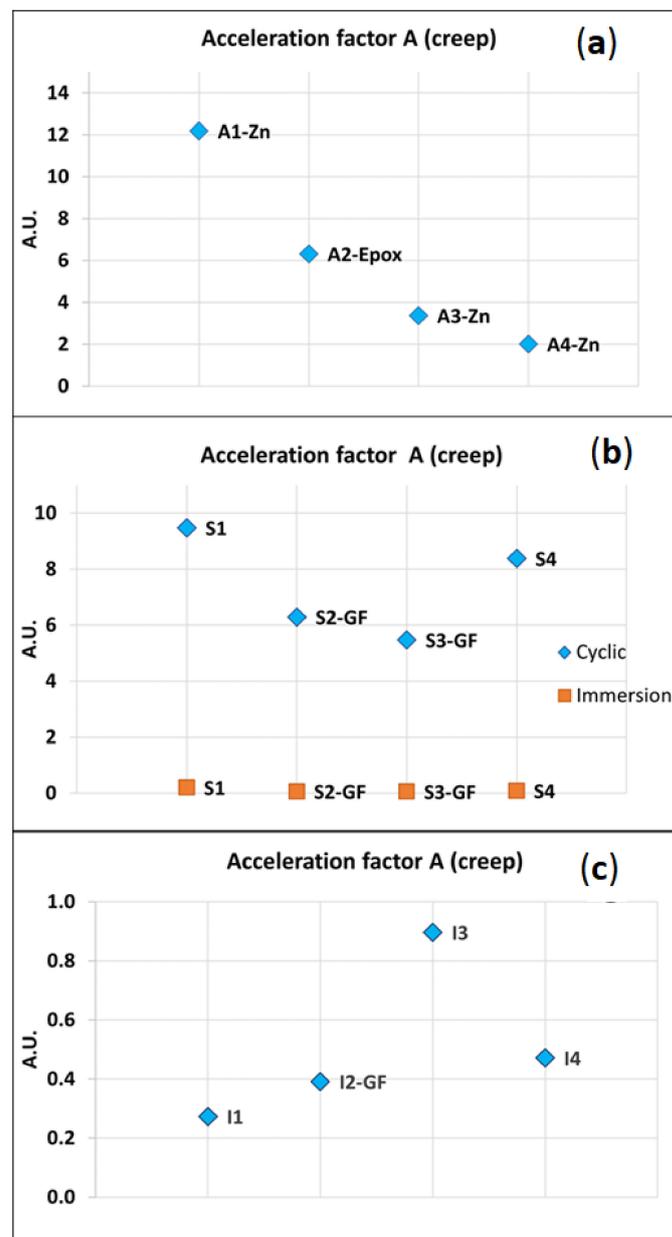

Figure 11. Acceleration factors for the coating systems for the atmospheric zone (**a**), splash zone (**b**), and submerged zone (**c**).

Table 11. Acceleration factors for all coatings.

Atmospheric Zone	A (creep)	Splash Zone	A (Creep) Cyclic Test	A (Creep) Immersion Test	Submerged Zone	A (Creep)
A1-Zn	12.19	S1	9.47	0.20	I1	0.27
A2-Epox	6.33	S2-GF	6.29	0.07	I2-GF	0.39
A3-Zn	3.38	S3-GF	5.47	0.06	I3	0.90
A4-Zn	2.02	S4	8.38	0.09	I4	0.47

As can be seen, the systems for the atmospheric zone are accelerated by different accelerating factors ranging approximately from 2 to 12. This is a broad range and indicates that the different coatings respond in a different manner to the accelerated tests and field exposure. A similar pattern, although in a smaller range, was observed for the cycling testing of the splash zone coatings. All coatings tested in the laboratory immersion test showed an acceleration factor < 1, which means that the test did not accelerate the aging. This once again raises the question whether this type of testing is relevant to all types oof coatings and does it make sense to carry it out.

From the data presented, it is evident that the accelerating aging did not accelerate with the same rate for all coatings. These results are very consistent with previously reported data on the acceleration effect [6,9,10] and confirm once again the importance of field testing in the evaluation of the protective effect of offshore coatings.

3.5. Analysis and Optimization of the Coating Process in the Coating Booth

One of the aims of this study was also to evaluate the potential of the coating solutions to be applied in a more time effective manner over the whole monopile and to provide the monopile manufacturer with the possibility of producing a greater number of monopiles per given period. Since the bottleneck of the coating application is the coating booth, we analyzed the time required for the steps carried out in the booth.

To complete the procedure, the coating process with a given coating system passes through several steps in the coating booth: coating application, curing, thickness inspection, and coating repairing, and these steps must be repeated for each layer of the coating system. The total duration of the application of a system depends on the duration of each of the steps and since some of the steps depends on the temperature, we are interested in quantifying how much time can be saved by controlling the temperature in the coating booth.

The coating Solutions 1, 2, 3, and 4 were analyzed in terms of the total time it takes to apply the coating onto the entire monopile (this includes coating the atmospheric, splash and submerged zones), which is designated $T_{Solution}$. Once the whole monopile is coated, it leaves the coating booth and another monopile can be transferred to the booth to be coated. Therefore, shorter $T_{Solution}$ is a prerequisite for a more efficient coating process since more monopiles can be coated on average. We analyzed this parameter for two application temperatures of 20 °C and 30 °C, and quantified the improvement that could be achieved.

To do so, we calculated $T_{Solution}$ at two different temperatures according to Equation (2), and $T_{Solution}$ is the sum of the total time required for the application of the coating system T_{Total} for each zone: atmospheric, splash, and submerged.

$$T_{Solution} = T_{Total}(\mathrm{A}) + T_{Total}(\mathrm{S}) + T_{Total}(\mathrm{I}) \tag{2}$$

Total application time T_{Total} of a given system is the sum of the time required for the application, curing, inspection, and repair of each layer of a coating system and it is calculated by Equation (3):

$$T_{Total} = \sum_{i=1}^{n}\left(T_{App,\,i} + T_{Over,\,i} + T_{Insp,\,i} + T_{Repair,\,i}\right) + T_{Handle} \tag{3}$$

where

- *i* is the index of the coating layer;
- T_{App} is the time of the application of a coating layer, which is a function of the area to be covered and is provided by a monopile manufacturer. It is considered that for the type of monopile depicted in Figure 1, the corresponding areas to be covered are as follows: atmospheric zone of 1000 m^2; splash zone of 300 m^2, submerged zone of 500 m^2;
- T_{Over} is the minimum overcoating interval, this is taken from the coating data sheet;
- T_{Insp} is the time required for the inspection of each coating layer, which is a function of the area and is provided by the monopile manufacturer: Atmospheric zone: 0.5 h, Splash zone: 0.15 h, Submerged zone: 0.25 h;
- T_{repair} is the time for the repair of the coating layer, and is given by the monopile manufacturer: atmospheric zone: 0.5 h, splash zone: 0.15 h, submerged zone: 0.25; and
- T_{Handle} is the dry to handle time, and is one for the whole system and is taken from the data sheet.

The corresponding data for each coating is listed in Table 12. Figure 12 shows the total time required for the painting of the whole monopile ($T_{Solution}$) with Solutions 1–4 at two different temperatures.
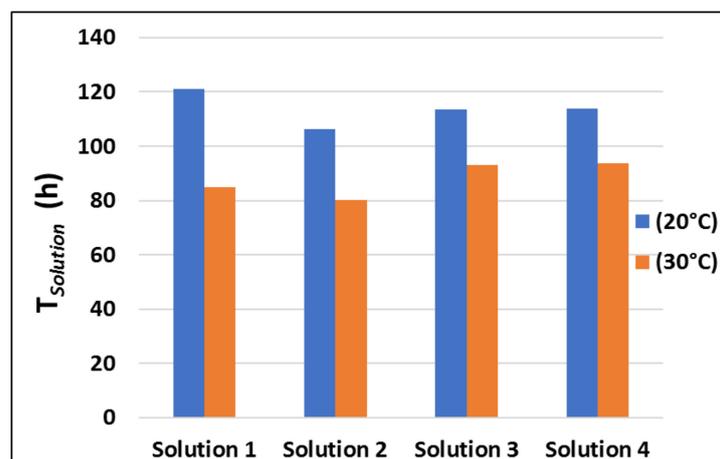

Figure 12. Time required for painting the whole monopile with the different solutions calculated at two different temperatures of 20 and 30 °C.

At 20 °C, Solution 1 took the longest time required (121 h) while Solution 2 had the shortest time (106 h). Raising the temperature by 10 °C contributed to a significant reduction in $T_{Solution}$, which was expected, since at higher temperature, the processes related to drying and curing are accelerated. However, for Solution 1, this acceleration was more pronounced than for the rest of the coatings and the time required to paint the whole monopile was reduced to 85 h. This allows the monopile manufacturer to quantify the improvement in coating rate as a function of the temperature in the booth and shows the degree a coating process can be accelerated for each solution. In this study, we observed around 25% time improvement for Solution 1, 10% for Solution 2, 7% for Solution 3, and 6% for Solution 4. This type of analysis is a useful tool for the monopile manufacturer in order to plan the coating activities and to be aware of how they can be made more time efficient. Furthermore, this data, coupled with the data from the laboratory testing and field exposure can serve as useful indicators for the selection of a given system.

Table 12. Parameters of the coatings related to their application time.

Coating Solution	Coating Systems	Application Duration T_{App} (h)	Minimum Overcoating Interval T_{Over} (h)		Dry to Handle Time T_{Handle} (h)		Total Application Time T_{Total} (h)		Application Time Whole Monopile $T_{Solution}$ (h)	
			(20 °C)	(30 °C)	(20 °C)	(30 °C)	(20 °C)	(30 °C)	(20 °C)	(30 °C)
Solution 1	A1-Zn	9.7	1.5	0.85						
		9.7	4	2	8	4	49.9	39.25		
		6	8	4						
	S1	2.91	8	4					121.12	84.97
		2.91	8	4	8	4	40.52	24.52		
		1.8	8	4						
	I1	4.85	3.5	2						
		4.85	8	4	8	4	30.7	21.2		
Solution 2	A2-Epox	9.7	5.5	3.5						
		9.7	5.5	3.5	8	3.5	55.4	42.4		
		6	8	3.5						
	S2-GF	2.91	5.5	3.5					106.32	80.32
		2.91	5.5	3.5	5.5	3	23.22	16.72		
	I2-GF	4.85	5.5	3.5						
		4.85	5.5	3.5	5.5	3	27.7	21.2		
Solution 3	A3-Zn	9.7	2	1.5						
		9.7	6	4.5	5	4.5	48.4	43.4		
		6	7	4.5						
	S3-GF	2.91	6	4.5					113.62	93.12
		2.91	6	4.5	7	4.5	34.52	26.52		
		1.8	7	4.5						
	I3	4.85	6	4.5						
		4.85	6	4.5	6	4.5	30.7	23.2		
Solution 4	A4-Zn	9.7	4	2						
		9.7	8	6	6	5	52.4	46.4		
		6	6	5						
	S4[2]	2.91	8	5					113.82	93.82
		2.91	8	5	6	5	28.72	21.72		
	I4[2]	4.85	8	5						
		4.85	8	5	6	7	30.7	23.2		

4. Conclusions

In this study, we investigated the corrosion protection of 12 coating systems for offshore monopiles and compared their performance under accelerated laboratory testing and real field exposure. The results showed that the aging of the coatings did not accelerate at the same rate in all coatings.

Furthermore, our results confirm that for the coatings exposed in the atmospheric zone, the Zn-rich primer is very important for achieving good corrosion protection. For the coatings exposed in the splash zone, we observed that the results after a one-year field exposure lay between those of cycling testing and those of immersion testing, and the

spread in the acceleration factor between the different coatings was less pronounced. For both splash and immersion coatings, we could clearly see that there were huge discrepancies between the results obtained in the seawater immersion test in the laboratory and field testing, with the laboratory test much less aggressive than the real offshore conditions. This observation confirms once again that the field exposure data provide valuable information in order to correctly assess the corrosion protection of the coatings and thus the expected lifetime of the offshore structure.

Furthermore, we performed an analysis of the time required for the application of the different coating solutions provided by four different manufacturers in order to quantify the possibility of speeding up the coating of the entire monopile by controlling the temperature. We observed that different solutions were affected by different degrees with a 10 °C temperature increase, and in some cases, an improvement in the time efficiency up to 25% could be expected.

Our results contribute to a better understanding of the issues related to testing and the qualification of corrosion protection coatings for offshore structures and provide useful insights for the selection of a coating solution at the industrial level.

Supplementary Materials: Supporting information is available at https://www.mdpi.com/article/10.3390/coatings12030384/s1 Figure S1: Visual appearance of the atmospheric zone test panels; Figure S2: Visual appearance of the splash zone test panels; Figure S3: Visual appearance of the submerged zone test panels; Table S1: Cathodic protection data for splash zone coatings; Table S2: Cathodic protection data for submerged zone coatings.

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