

# Accelerated Prediction Methodologies to Predict the Outdoor Exposure Lifespan of Galvannealed Steel

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Generally, atmospheric corrosion is the electrochemical degradation of metal that can be caused by various corrosion factors of atmospheric components and weather, as well as air pollutants. Specifically, moisture and particles of sea salt and sulfur dioxide are major factors in atmospheric corrosion. Using galvanized steel is one of the most efficient ways to protect iron from corrosion by zinc plating on the surface of the iron. Galvanized steel is widely used in automobiles, building structures, roofing, and other industrial structures due to their high corrosion resistance relative to iron. The atmospheric corrosion of galvanized steel shows complex corrosion behavior, depending on the plating, coating thickness, atmospheric environment, and air pollutants. In addition, corrosion products are produced in different types of environments. The lifespans of galvanized steels may vary depending on the use environment. Therefore, this study investigated the corrosion behavior of galvannealed steel under atmospheric corrosion in two locations in Korea, and the lifespan prediction of galvannealed steel in rural and coastal environments was conducted by means of the potentiostatic dissolution test and the chemical cyclic corrosion test.

**Keywords:** Galvannealed steel, Outdoor exposure test, Atmospheric corrosion, Lifespan prediction

## 1. Introduction

Parameters to affect atmospheric corrosion can be divided into chemical and physical factors [1-9]. Chemical factors include oxygen, ozone, moisture, sulfur dioxide, salt, dust, acid rain, inclusion on the surface, and other gases. Physical factors are mainly temperature, wind intensity, and sunlight. These factors may be changeable with seasons and the natural environment, and these climate changes influence the corrosion behavior of metals and alloys. In general, the environments in which the metals and alloys are applied can be classified into coastal, industrial, urban, and rural areas [9-13]. However, it should be noted that the above classification is greatly simplified. The applied environment can have a large effect on the lifespan of every metal and alloy, and thus the estimation of lifespan needs to fully understand and take into account the environment [14].

When metallic materials are used or exposed outdoors, degradation can take place by the natural environment, such as sunlight, humidity, rain, dew condensation, and pollutant gases in the air, and thus weather resistance, cor-

rosion resistance, and durability are lowered. Therefore, in order to measure the properties in the air, the optimum method is the atmospheric outdoor exposure test [15-18]. The atmospheric outdoor exposure test evaluates the effect of the environmental factors ( $\text{Cl}^-$ ,  $\text{CO}$ ,  $\text{NO}_x$ ,  $\text{SO}_x$ ,  $\text{O}_3$ ) including weather factors (temperature, humidity, quantity of solar radiation, snow, and rain) on the degradation of industrial products (automobile, train, tire, bridge, road facilities, metals, textile, rubber, antenna, cables etc.) that are used or installed at outdoor sites. Because the outdoor exposure test is one of the essential reliability evaluation methods to improve the quality, and estimate the lifespan of new materials or products, it is considered to be very important. Recently, our group reported the atmospheric corrosion of galvanized steels in Korea [19,20]; when the exposure time was increased, the content of Zn from galvannealed steel - GA surface decreased while the contents of iron and oxygen tended to increase [19]. With increasing exposure times, the galvannealed steel - GA specimen became blackened by the formation of zinc oxide, and red coloration was increased by the formation of red rust. As the exposure time of galvanized steel - GI specimen increased, the surface proceeded to blacken, but no red rust was formed and the color did not change significantly.

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**Table 1** Cyclic test condition for simulated atmospheric corrosion test [21]

	Process	Details
Step 1	Spray	Temperature: 30 °C Spray Time: 10 min Holding time : 20 min
Step 2	Humid atmosphere	Temperature: 50 °C Relative humidity: 80%RH Time: 120 min
Step 3	Washing	Temperature: Room temperature Relative humidity: 100%RH Time : 5 s
Step 4	Drying	Temperature: 40 °C Relative humidity: 35%RH Time: 120 min

Regardless of the outdoor exposure area or the specimen, longer exposure times led to lower glossiness, and this behavior appears to be influenced by the formation of zinc oxide [20]. Even though the research about the atmospheric corrosion of galvanized steels has been continued for a long time, there is little method to predict the lifespan of the steel used in outdoor environments.

Therefore, this work performed the outdoor exposure test of galvanized steel. Two of the exposure sites representing the rural and coastal environments were selected to develop the methodologies to predict the outdoor exposure lifespan of galvanized steel. Two kinds of prediction method were induced by the electrochemical and the chemical approaches.

## 2. Experimental Methods

### 2.1 Outdoor exposure test

The test material is the galvanized steel - GA (Zn-Fe). The exposure sites are 2 locations that represent the rural (Andong) and coastal (Busan) environments in Korea. The exposure durations are (1, 6, 12, 24, and 36) months. After the test, the corrosion rate was calculated through weight loss measurement, after the removal of corrosion products or inclusions. Chemical cleaning was performed according to KS D ISO 8407 [22], including 1st step (4 min immersion in 70 °C, 10% ammonium chloride solution) and 2nd step (5 min immersion in 25 °C ammonium persulfate).

### 2.2 Anodic polarization test

Specimens were cut to a size of 1.5 mm × 1.5 mm and exposed 1 cm<sup>2</sup> of area using a flat cell. A polarization test was performed using a potentiostat (DC 105, Gamry Instruments), the reference electrode was a saturated calo-

mel electrode (SCE), and the counter electrode was Pt wire. Test solution was simulated acid rain for rural environment (1.2 mL HNO<sub>3</sub> + 1.73 mL H<sub>2</sub>SO<sub>4</sub> in 1 L distilled water and pH 5 was controlled using 10% NaOH) and chloride added simulated acid rain for coastal environment (5% NaCl + 1.2 mL HNO<sub>3</sub> + 1.73 mL H<sub>2</sub>SO<sub>4</sub> in 1 L distilled water and pH 5 was controlled using 10% NaOH). Test temperature was room temperature. The test solution was deaerated using N<sub>2</sub> gas (200 mL/min at 30 min). The scanning rate was 0.33 mV/sec.

### 2.3 Potentiostatic dissolution test

Specimens were cut to a size of 1.5 mm × 1.5 mm and exposed 1 cm<sup>2</sup> of area using a flat cell. The potentiostatic dissolution test was performed on +200 mV (SCE), and various diluted acid rains were used. The reference electrode was a saturated calomel electrode (SCE), and the counter electrode was Pt wire.

### 2.4 Chemical cyclic corrosion test

The chemical cyclic corrosion test was performed using a salt sprayer tester and constant temperature/constant humidity tester. One cyclic test includes spray, humid atmosphere, washing, drying process, and the detailed test condition is shown in Table 1. Test solution was chloride added simulated acid rain (5% NaCl + 1.2 mL HNO<sub>3</sub> + 1.73 mL H<sub>2</sub>SO<sub>4</sub> in 1 L distilled water and pH 5 was controlled using 10% NaOH). Dilution ratio was 1:2.

### 2.5 Surface analysis

After the exposure test, the corrosion rate was calculated through weight loss measurement, after the removal of corrosion products or inclusions. Chemical cleaning was performed according to KS D ISO 8407 [22], including 1st step (4 min immersion in 70 °C, 10% ammonium chloride solution) and 2nd step (5 min immersion in 25 °C ammonium persulfate). Chemical composition on the surface after chemical cleaning was analyzed using a SEM-EDS (VEGAILMU, Tescan). After potentiostatic dissolution test and chemical cyclic corrosion test, chemical composition on the surface was also analyzed using a SEM-EDS.

## 3. Results and Discussion

### 3.1 Electrochemical approach to induce the lifespan prediction of galvanized steel

In order to induce the lifespan prediction equation, anodic polarization and potentiostatic dissolution tests were performed. For test solution, simulated acid rain for rural environment and chloride added simulated acid rain for

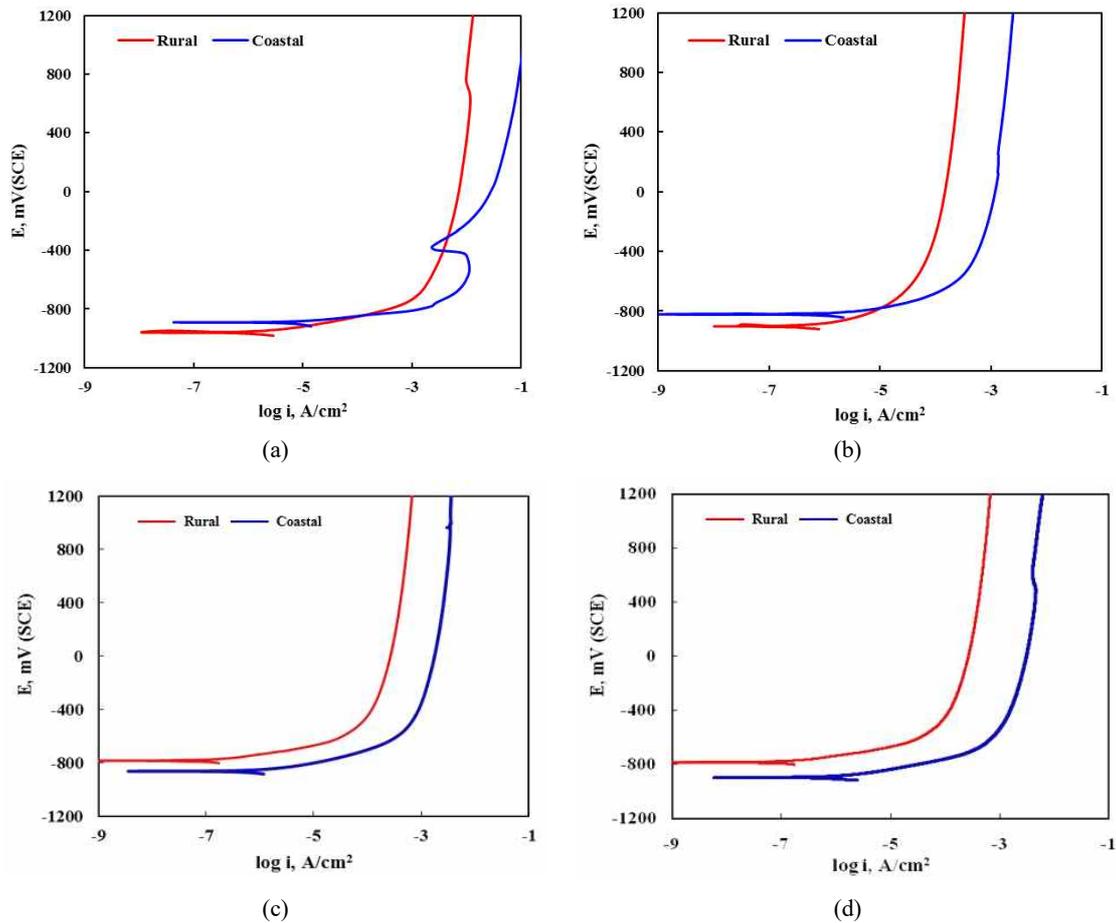


Fig. 1 Effect of dilution ratio on the anodic polarization behavior of galvanized steel - GA in simulated acid rain for rural area and chloride added simulated acid rain for coastal area; (a) no dilution, (b) dilution ratio 1:100, (c) dilution ratio 1:50, (d) dilution ratio 1:25.

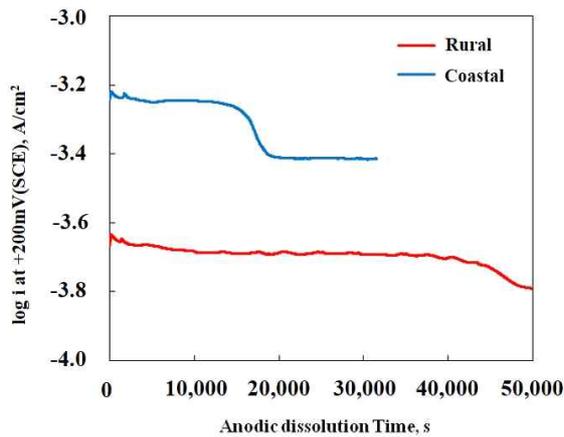
coastal environment were used since atmospheric corrosion could be affected by  $\text{Cl}^-$  and  $\text{SO}_2/\text{SO}_4^{2-}$ . These experiments aim to find the relationship between outdoor exposure test and electrochemical test.

Test material was commercial galvanized steel – GA. The simulated acid rain for rural area [‘rural’] was (1.2 mL  $\text{HNO}_3$  + 1.73 mL  $\text{H}_2\text{SO}_4$ )/1 L, its pH was controlled as 5 using 10% NaOH and the chloride added simulated acid rain [‘coastal’] was (5% NaCl + 1.2 mL  $\text{HNO}_3$  + 1.73mL  $\text{H}_2\text{SO}_4$ )/1 L, its pH was controlled as 5 using 10% NaOH.

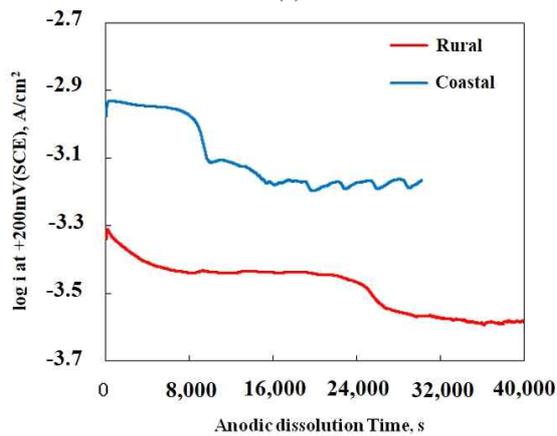
Fig. 1 shows the anodic polarization curves of galvanized steel in simulated acid rain and chloride added simulated acid rain with various dilution ratio. With the anodic polarization, anodic current density was increased and the current densities of chloride added simulated acid rain were larger than those of simulated acid rain, regardless of dilution ratios. No solution could be used to induce

the prediction equation because of very fast dissolution rate.

Fig. 2 reveals the potentiostatic dissolution test of galvanized steel. Potentiostatic dissolution was performed at +200 mV(SCE) with anodic dissolution time in simulated acid rain (Rural and Coastal areas). Fig. 2a is for the dilution ratio 1:50 and Fig. 2b is for the dilution ratio 1:25. With anodic dissolution time, it can be observed that the current density takes step-down after a constant current; In the case of the dilution ratio of 1:50, the step-down was observed after 45,000 seconds for ‘rural’ and was observed after 15,000 seconds for ‘coastal’. In the case of the dilution ratio of 1:25, the step-down was observed after 24,000 seconds for ‘rural’ and was observed after 8,000 seconds for ‘coastal’. Surface analysis at each time confirmed that this step-down was induced by the dissolution of iron in the matrix because the Zn-Fe coating was thoroughly dissolved. Among 3 kinds of dilu-



(a)



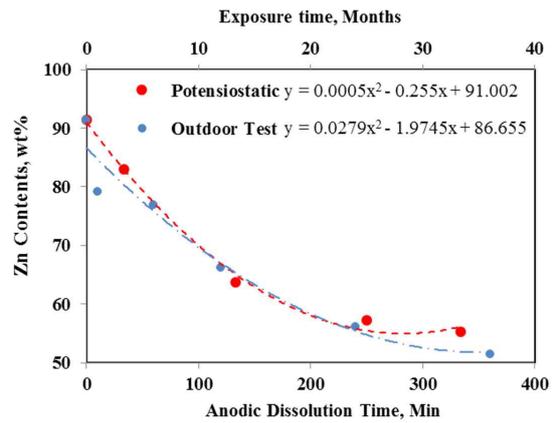
(b)

Fig. 2 Corrosion current density of galvanized steel – GA with potentiostatic dissolution time at +200 mV(SCE) in simulated acid rain for rural area and chloride added simulated acid rain for coastal area; (a) dilution ratio 1:50, (b) dilution ratio 1:25.

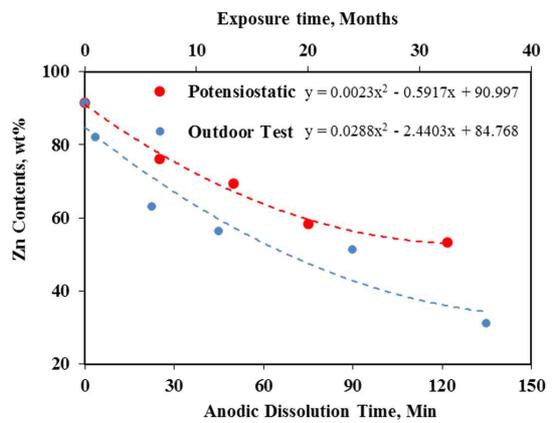
tion ratio’s solution, the dilution ratio of 1:25 after lots of preliminary tests was chosen to find the relationship between outdoor exposure test and electrochemical test.

Fig. 3 shows the effect of test time on the Zn content of the surface of galvanized steel by the outdoor exposure test and the anodic dissolution test in simulated acid rain with the dilution ratio of 1:25. Fig. 3a is for the rural area – Andong and Fig. 3b is for the coastal area – Busan. In the figures, trend line and trend equation were shown. The surface analysis and surface appearance after the outdoor exposure test were already reported in other paper [19,20] and we plotted Zn contents with different style in Fig. 3. It is interesting that Zn contents with potentiostatic dissolution time were similar to those of outdoor exposure test with exposure time.

From two trend equations, we can obtain the time to show the same Zn content in the outdoor exposure test and potentiostatic dissolution test. Fig. 4 was plotted from



(a)



(b)

Fig. 3 Effect of test time on the Zn content of the surface of galvanized steel - GA by the outdoor exposure test and the anodic dissolution test in simulated acid rains with dilution ratio of 1:25; (a) rural area, (b) coastal area.

this procedure. Fig. 4 shows the relationship between anodic dissolution time and outdoor exposure time to reveal the same Zn content on the surface of galvanized steel. Fig. 4a is for the rural area and Fig. 4b is for the coastal area. As shown in figures, two lifespan prediction equations were derived.

For rural area,

$$\text{Outdoor exposure time (months)} = 0.10 \times \text{potentiostatic dissolution time (minutes)} - 1.04.$$

For coastal area,

$$\text{Outdoor exposure time (months)} = 0.16 \times \text{potentiostatic dissolution time (minutes)} - 0.70.$$

### 3.2 Chemical approach to induce the lifespan prediction of galvanized steel

Another approach for deriving the lifespan prediction equation was the chemical cyclic corrosion test. Fig. 5 shows the effect of test time on the Zn content of the

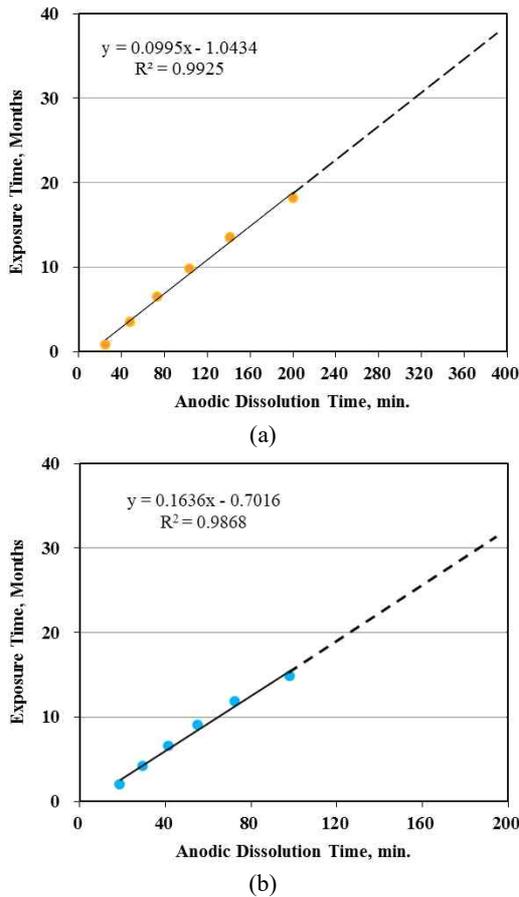


Fig. 4 Relationship between anodic dissolution time and outdoor exposure time to reveal the same Zn content on the surface of galvanized steel - GA; (a) Rural area, (b) Coastal area.

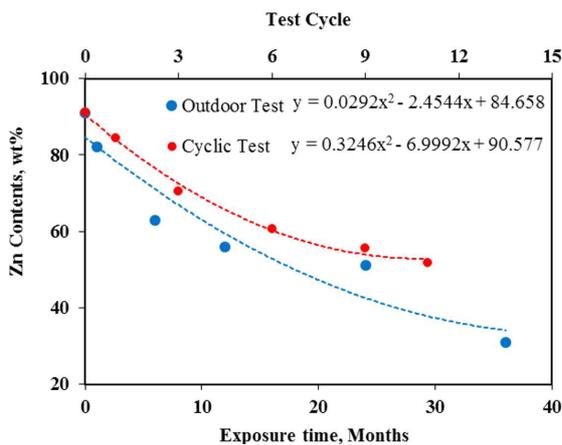


Fig. 5 Effect of test time on the Zn content of the surface of galvanized steel - GA by the outdoor exposure test and the cyclic corrosion test for coastal area.

surface of galvanized steel - GA by the outdoor exposure test and the cyclic corrosion test for the coastal area. The outdoor exposure durations were (1, 6, 12, 24, and 36) months and after each exposure duration, chemical

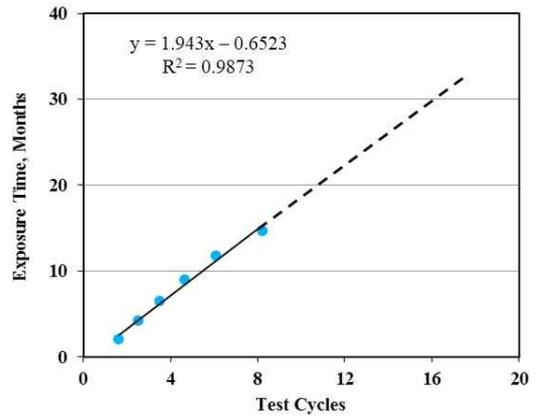


Fig. 6 Relationship between corrosion test cycles and outdoor exposure time to reveal the same Zn content on the surface of galvanized steel - GA for coastal area.

composition was analyzed on the surface. The cyclic corrosion test solution was chloride added simulated acid rain with the dilution ratio of 1:2. After 1, 3, 6, 9, 11 cyclic tests, chemical composition was analyzed on the surface. As shown in Fig. 5, a similar trend was observed in the outdoor exposure test and cyclic corrosion test, and two trend equations were also shown in the figure.

From two trend equations, we can obtain the time to show the same Zn content in the outdoor exposure test and a cyclic corrosion test. Plotting was done with this procedure in Fig. 6. Fig. 6 shows the relationship between cyclic corrosion test cycle and outdoor exposure time to reveal the same Zn content on the surface of galvanized steel for the coastal area. As shown in figures, a lifespan prediction equation for the coastal environment was derived.

Outdoor exposure time (months) =  $1.94 \times$  cyclic corrosion test (cycles) - 0.65.

#### 4. Conclusions

This work performed the outdoor exposure test of galvanized steel - GA. Two of exposure sites representing the rural (Andong) and coastal (Busan) environments in Korea were selected to develop the methodologies to predict the outdoor exposure lifespan of galvanized steel. Two kinds of prediction method were induced by the electrochemical and chemical approaches;

- (1) In order to find out the atmospheric corrosion lifespan by outdoor exposure test, the very long test time is needed. However, accelerated electrochemical and chemical methods can be induced by the selection of electrochemical condition or chemical cyclic test condition with the combination of

the appropriate test solution.

- (2) Using a potentiostatic dissolution test in simulated acid rain for rural or coastal environments, two lifespan prediction equation were derived; For rural area, “Outdoor exposure time (months) =  $0.10 \times$  potentiostatic dissolution time (minutes) – 1.04” and for coastal area, “Outdoor exposure time (months) =  $0.16 \times$  potentiostatic dissolution time (minutes) – 0.70”
- (3) Using a chemical cyclic corrosion test in simulated acid rain for the coastal environment, a lifespan prediction equation for coastal environment was derived; “Outdoor exposure time (months) =  $1.94 \times$  cyclic corrosion test (cycles) – 0.65”

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