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# Atmospheric Corrosion Behavior of Weathering Steel Exposed to the Outdoors for 10 Years in Korea

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Steel structures exposed to the outdoors experienced several types of corrosion, which may reduce their thickness. Since atmospheric corrosion can induce economic losses, it is important to consider the atmospheric corrosion behavior of a variety of metals and alloys. This work performed outdoor exposure tests for 10 years at 14 areas in Korea and calculated the atmospheric corrosion rate of weathering steel. This paper discussed the atmospheric corrosion behavior of weathering steel based on various corrosion factors. The average corrosion rates in coastal, industrial, urban, and rural areas were found to range from (2.83 to 4.23) μm/y, (2.99 to 4.23) μm/y, (1.72 to 3.14) μm/y, and (1.57 to 2.85) μm/y respectively. It should be noted that the maximum corrosion rate was about 6.0 times greater than the average corrosion rate. Regardless of the exposure sites, the color differences were increased, but the glossiness was reduced and there was no relationship between the corrosion rate and environmental factors and the glossiness.

***Keywords:*** *Weathering steel, Atmospheric corrosion, Corrosion rate, Color difference, Glossiness*

## 1. Introduction

Steel structures facing outdoor exposure experience several types of corrosion, and their thickness may be reduced. Since atmospheric corrosion can induce economic losses, the atmospheric corrosion behavior of a variety of metals and alloys should be examined [1-6]. Atmospheric corrosion can be induced by the periodical variation of temperature, humidity, and dissolved oxygen, at which point water film forms on the surface and induces corrosion of metals and alloys [7,8]. Other corrosive species which may affect atmospheric corrosion include $SO_2$, $Cl^-$, solid particles, etc. [6].

Since the corrosive atmosphere varies with location, corrosion behavior differs between different areas, and a different corrosion product may be formed [9]. Based on these data, a simple classification scheme of five corrosivity classes was established for each metal [10], and these five corrosivity categories can be roughly translated into the following five outdoor situations listed in descending order of corrosivity: industrial, tropical marine, temperate marine, urban and rural [11].

Corrosivity categories in Korea are low when classified by $SO_2$ and chloride deposition, but those in the Korean peninsula are high when classified by TOW (Time of Wetness) [10,12]. We have reported the results of outdoor exposure testing of carbon steel for 10 years in Korea [10]. In coastal areas, the average corrosion rate was obtained from (2.83 to 4.23) μm/y, and the maximum corrosion rate was determined to be from (26.6 to 31.7) μm/y. In industrial areas, the average corrosion rate was obtained from (2.99 to 4.23) μm/y, and the maximum corrosion rate was determined to be from (33.9 to 35.3) μm/y. In urban areas, the average corrosion rate was obtained from (1.72 to 3.14) μm/y, and the maximum corrosion rate was determined to be from (6.2 to 21.0) μm/y. In rural areas, the average corrosion rate in rural area was obtained from (1.57 to 2.85) μm/y, and the maximum corrosion rate was determined to be from (7.0 to 23.0) μm/y. On the other hand, regardless of the exposure sites, the color differences were increased, and the glossiness was decreased, and there was no relationship between the corrosion rate and environmental factors and the glossiness.

The inappropriate use of structural carbon steel without

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corrosion protection in the outdoor environment and other reasons has led to the development of new types of low-alloy steels [13]. Weathering steels, also known as low-alloy steels, are steels with a carbon content of less than 0.2 wt% to which Cu, Cr, Ni, P, Si and Mn are mainly added as alloying elements to a total of no more than 3–5 wt% [14]. The main applications for weathering steel include civil structures such as bridges and other load-bearing structures, road installations, guide rails, ornamental sculptures and streetlamps. When weathering steels are exposed to atmosphere, a homogeneous and adherent rust layer is formed on their surfaces [15-19]. The rust layer forms a dense oxide layer between the rust layer and the base metal, which prevents oxygen and water from penetrating the base metal and acts as a protective film against the external atmosphere to inhibit corrosion [20,21]. A surface rust layer with a duplex structure is normally formed which consisting of an outer layer of γ-FeOOH and an inner layer of nano-sized α-FeOOH containing a considerable amount of Cr [22]. In weathering steel, the rust layer of the weathering steel has cation selectivity in a low chloride ion atmosphere, so the rust layer densely protects the weathering steel to inhibit corrosion [23-25], but in a high chloride atmosphere, the rust layer becomes porous, which facilitates the transport of chloride ions from the outside, thus accelerating corrosion [26].

Therefore, in this work, the outdoor exposure test was conducted for 10 years at 14 areas in Korea, and the atmospheric corrosion rate of weathering steel was calculated. The atmospheric corrosion behavior of weathering steel is discussed based on the various corrosion factors.

## 2. Experimental Methods

### 2.1 Outdoor Exposure Test

Table 1 shows the chemical composition of the weathering steel used in this work. The specimen was cut to a size of 200 mm × 200 mm × 1.54 mm and installed to have a slope of 45º under outdoor exposure conditions. It was installed on flat ground where the amount of sunlight was always constant, in airy conditions, and where almost no buildings existed. For outdoor exposure sites, 4 kinds of categories of coastal, industrial, urban, and rural environments were selected. The outdoor exposure sites were installed at a total 14 locations in Busan, Seosan, Gwangyang, Incheon, Pohang, Asan, Ansan, Goyang, Seoul, Suwon, Gwangju, Andong, Jochiwon, and Chuncheon [27].

After the outdoor exposure test, the method of KS D 9226 was used to measure the average corrosion rate of weathering steel specimens [28]. To remove the corrosion product, distilled water was added to 400 g ammonium citric acid to prepare 2,000 mL, and the specimen immersed at 80 ºC for 20 min to remove the corrosion product. After the chemical cleaning, the weight of the weathering steel specimen was measured, and the average corrosion rate was obtained by substituting the weight change before and after outdoor exposure into the following equation.

$$Corrosion\ rate,\ \mu m/y\ =\ \frac{\Delta W}{A\rho T}$$

ΔW = Weight loss (mg), $\rho_{Fe}$ = 7.86 (g/cm$^3$)
A = Exposed area (cm$^2$), T = Time (h)
*ΔW = a-b
a = Weight of the specimen before exposure test (mg)
b = Weight of the specimen by chemical cleaning after exposure test (mg)

After the outdoor exposure test, to measure the maximum corrosion rate of the weathering steel specimen, the corroded weathering steel specimen was cut to a size of 15 mm × 15 mm × 1.54 mm, ground with #2000 SiC paper, and then mirror-finished with 3 μm diamond paste. The maximum corrosion rate was obtained by measuring the minimum residual thickness excluding the corrosion product of the cross-section of the weathering steel specimen, using optical microscopy (AXIOTECH 100 HD,

**Table 1. Chemical composition of the weathering steel used in the test (wt%)**

| C | Si | Mn | P | S | Cr | Ni | Cu | Fe |
|---|---|---|---|---|---|---|---|---|
| 0.0703 | 0.46 | 0.402 | 0.1005 | 0.0048 | 0.39 | 0.14 | 0.27 | bal. |

ZEISS, Oberkochen, Germany). To collect atmospheric corrosive environmental factors, the data from the Meteorological Administration of Korea were used to investigate the TOW, $SO_2$ concentration, and $NO_2$ concentration from 2009 to 2018, and then the average values were calculated and displayed.

## 2.2 Surface appearance and Corrosion product analysis

### 2.2.1 Chromaticity measurement

The chromaticity of weathering steel was measured by color difference meter (SP64, X-rite, USA). As a measurement standard for chromaticity, L*a*b* values determined by the Commission international de l'éclairage (CIE) were used [29]. Fig. 1 shows the spatial representation of the CIE LAB color space. In the L*a*b* color space, L* indicates lightness, and a* and b* are chromaticity coordinates. a* and b* are color directions: +a* is the red axis, –a’ is the green axis, +b* is the yellow axis, and –b* is the blue axis [30]. For the chromaticity measurement method, after washing the exposed specimen in running water with a soft brush, the central part of the specimen was positioned on a finder, and then repeatedly measured three times to obtain the L*, a*, and b* values, using the average value. In addition, the values of ΔL*, Δa*, and Δb* were calculated to confirm the overall color change, and the color difference value ΔE*ab was calculated using the following equation [31].

$$\Delta E^*ab = \sqrt{(\Delta L^*)^2 + (\Delta a^*)^2 + (\Delta b^*)^2}$$

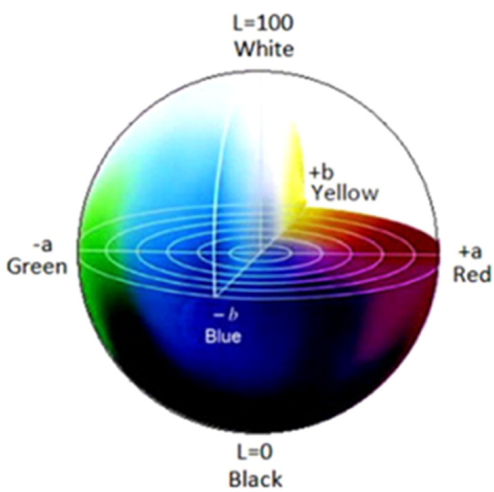


**Fig. 1. CIE LAB color chart [30]**

### 2.2.2 Gloss measurement

The gloss of weathering steel was measured by gloss meter (Micro-TRI-glass, BTK Ins., Germany). It was measured by using the method defined in the measurement method of KS L 2405 [32], and the international standard ASTM D 523 for gloss standard measurement [33]. Before measuring the gloss, foreign substances and corrosion products on the surface were removed by using a soft brush in flowing water, and then the average value was calculated by repeating measurements 5 times at a measuring angle of 60º.

### 2.2.3 Cross-section analysis

After the outdoor exposure test, the specimen was cut to a size of 15 mm × 15 mm × 1.54 mm, the specimen was polished using #2000 SiC paper, and then mirror-finished with 3 μm diamond paste. The cross-sectional shape and composition were observed at X400 magnification using SEM-EDS (MIRA3XMH, Tescan, Brno, Czech Republic) equipment and the contents of Fe and O in the cross-section were measured.

# 3. Results and Discussion

## 3.1 Atmospheric corrosion of weathering steel with outdoor exposure time

Fig. 2 shows the average corrosion rate of weathering steel with outdoor exposure time in Korea for 10 years. Fig. 3a shows the rates of Busan and Seosan as the coastal areas; Fig. 2b shows the rates of Gwangyang and Pohang near the coastline as the industrial areas; Fig. 2c shows the rates of Suwon, Gwangju, Seoul, Ansan, and Incheon as the urban areas; and Fig. 2d shows the rates of Asan, Goyang, Chuncheon, Andong, and Jochiwon as the rural areas. Regardless of the exposure areas, the average corrosion rates of the exposure test were very high in the early stage; however, as the exposure time increased, the average corrosion rate decreased. Since Busan and Seosan (coastal area) as well as Gwangyang and Pohang (industrial area) are all adjacent to the coastline, the initial average corrosion rates in those locations were high due to the chloride in the air, aside from the rural areas. The average corrosion rate in urban areas was relatively low in the rest of the region aside from Gwangju. In the case of the Gwangju area, it is an inland area far from the

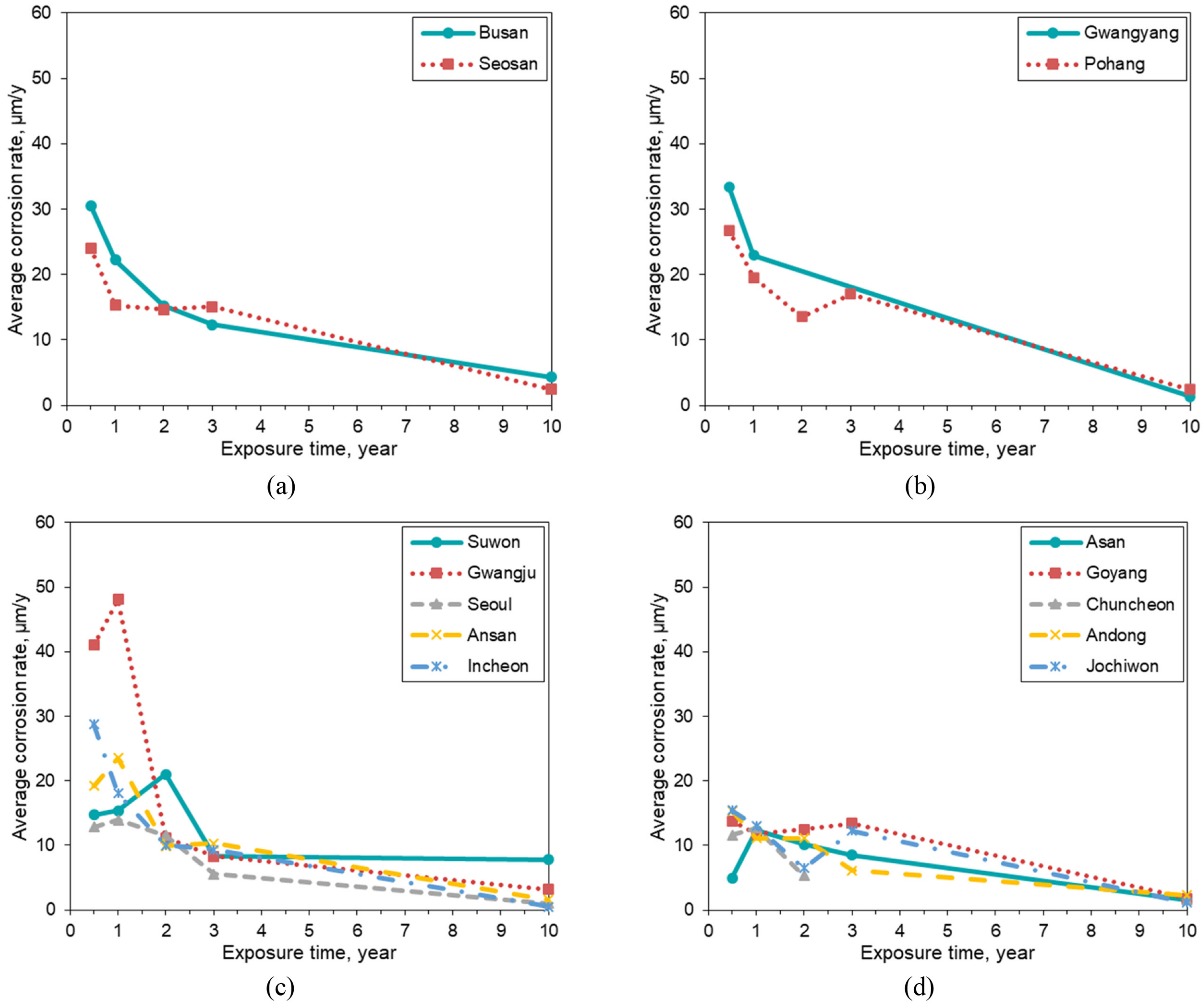


**Fig. 2. Average corrosion rates of weathering steel with outdoor exposure time in Korea for 10 years: (a) Coastal areas, (b) Industrial areas, (c) Urban areas, and (d) Rural areas**

coast, but it shows a high corrosion rate in the initial stage. However, rural areas showed lower average corrosion rates than other areas (urban, coastal, industrial).

Fig. 3 shows cross-sections of weathering steel after the outdoor exposure test for 10 years in Korea. Regardless of the exposure area, little localized corrosion could be observed, even though there was general corrosion. However, the extent of localized corrosion of weathering steel was quite lower than that of carbon steel [10]. In other words, the corrosion depth can differ between different exposure areas. The maximum corrosion rate was determined by observing the thinned cross section using an optical microscope, and the average corrosion rate was obtained according to KS DISO 9226 [28].

### 3.2 Relationship between atmospheric corrosion rate and environmental factors

Fig. 4 shows the atmospheric corrosion rate of weathering steel exposed for 10 years in Korea in terms of distance from the coast. Fig. 4a shows the average corrosion rate while Fig. 4b shows the maximum corrosion rate. As the exposed area was nearer to the shore, the average corrosion rate increased very slightly, but the maximum corrosion rate increased. The trend equation between the average corrosion rate and the distance from the coast was $y = -0.061\ln(x) + 2.0388$, and the trend equation between the maximum corrosion rate and the distance from the coast was $y = -7.047\ln(x) + 54.72$.

Fig. 5 shows the relationship between the time of

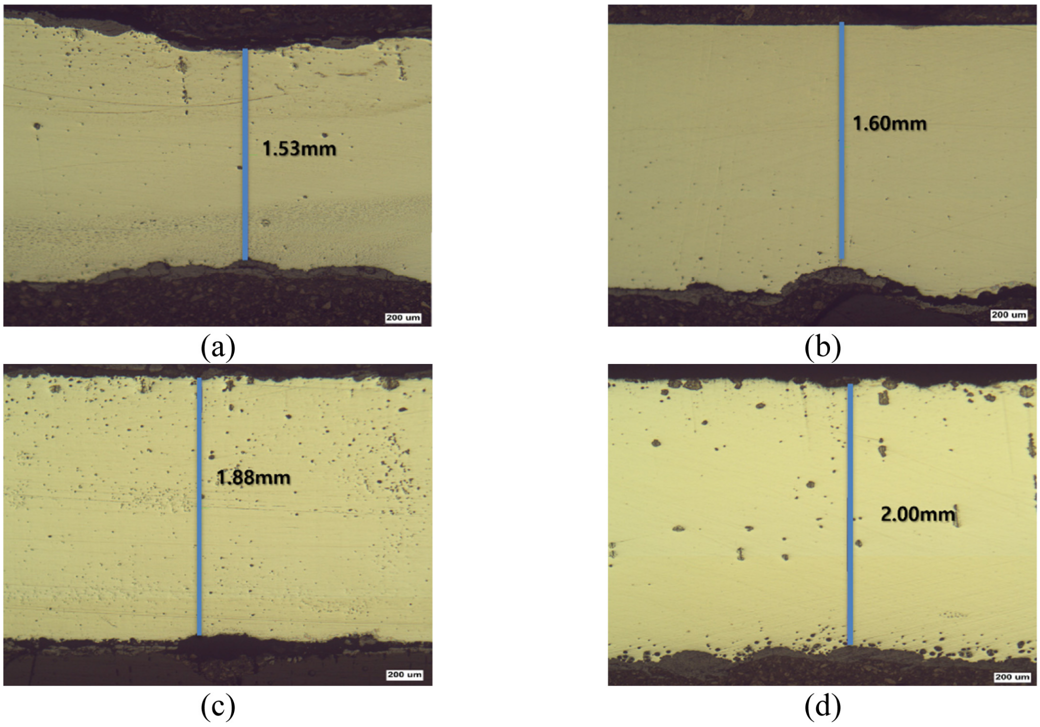


**Fig. 3. Localized corrosion of weathering steel exposed for 10 years in Korea: (a) Coastal area (Seosan), (b) Industrial area (Gwangyang), (c) Urban area (Seoul), and (d) Rural area (Andong)**

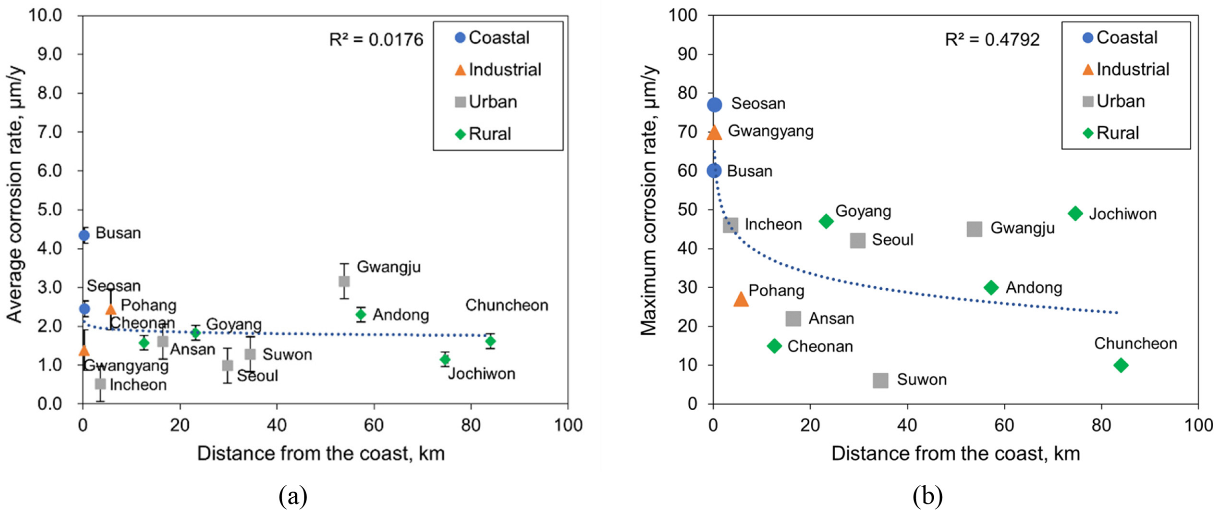


**Fig. 4. Atmospheric corrosion rate of weathering steel exposed for 10 years in Korea with the distance from the coast: (a) Average corrosion rate, and (b) Maximum corrosion rate**

wetness and the atmospheric corrosion rate of weathering steel exposed for 10 years in Korea. With increasing time of wetness, the average corrosion rate and the maximum corrosion rate were almost constant, even though there was substantial fluctuation. The trend equation between the average corrosion rate and the time of wetness was $y = -0.343\ln(x) + 4.6116$, while the trend equation between the maximum corrosion rate and the time of wetness was $y = -5.581\ln(x) + 83.029$. However, it should be noted that the determination coefficients of the trend equations were very low.

Fig. 6 depicts the relationship between $SO_2$

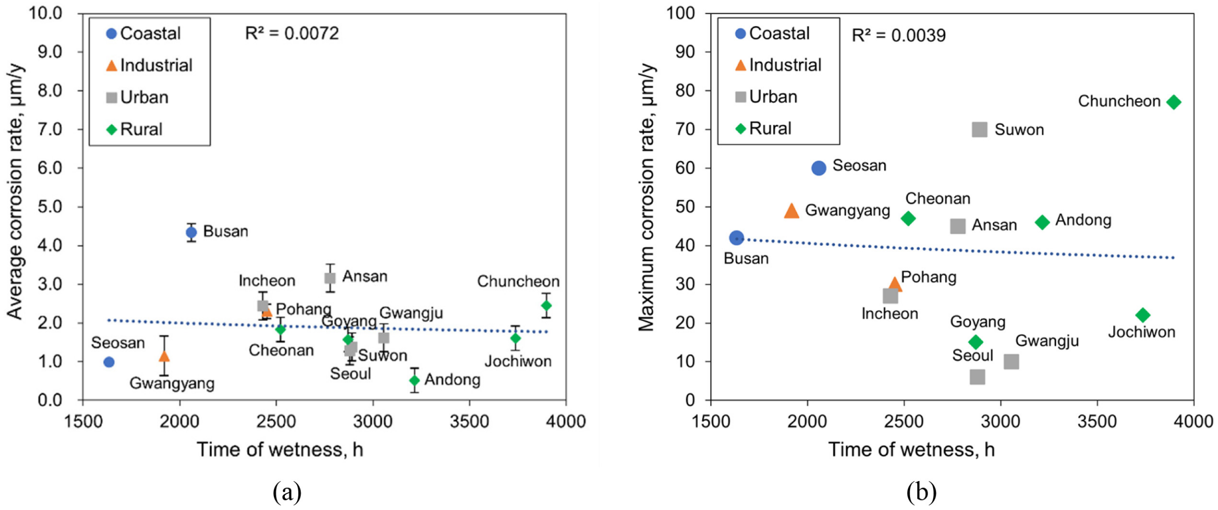


**Fig. 5. Relationship between the time of wetness and the atmospheric corrosion rate of weathering steel exposed for 10 years in Korea: (a) Average corrosion rate, and (b) Maximum corrosion rate**

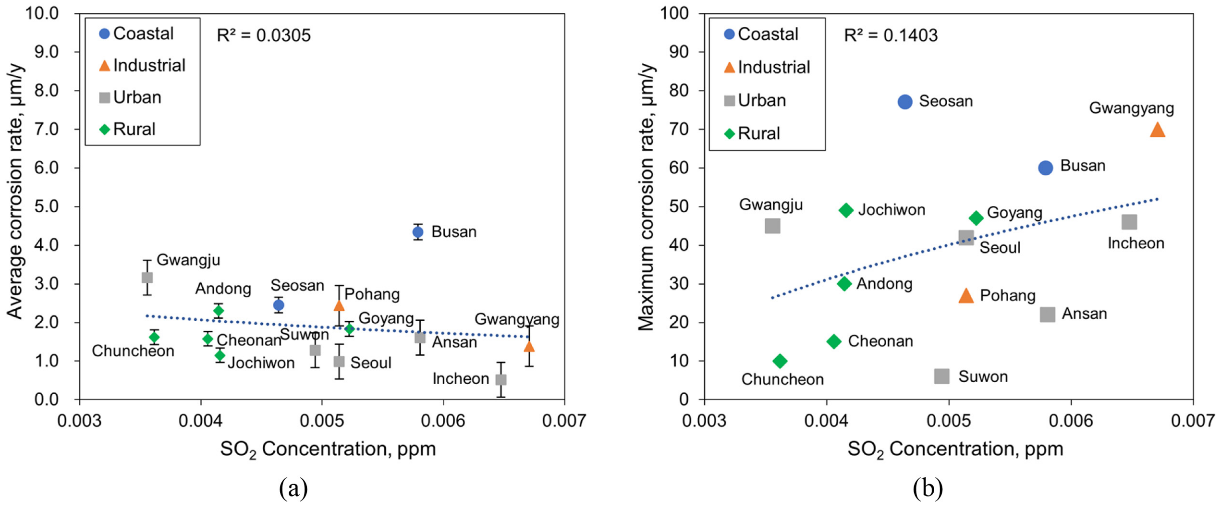


**Fig. 6. Relationship between $SO_2$ concentration and the atmospheric corrosion rate of weathering steel exposed for 10 years in Korea: (a) Average corrosion rate, and (b) Maximum corrosion rate**

concentration, and the atmospheric corrosion rate of weathering steel exposed for 10 years in Korea. As the $SO_2$ concentration increased, the average corrosion rate was almost constant, but the maximum corrosion rate increased significantly, despite the large fluctuation. The trend equation between the average corrosion rate and the time of wetness was $y = -0.85\ln(x) - 2.6245$, and the trend equation between the maximum corrosion rate and the time of wetness was $y = 40.29\ln(x) + 253.57$. However, it should be noted that the determination coefficients of the trend equations were slightly low.

Fig. 7 shows the relationship between the $NO_2$ concentration, and the atmospheric corrosion rate of weathering steel exposed for 10 years in Korea. As detailed above, although it has been known that the environmental factors increase the atmospheric corrosion rate, there was no relationship between $NO_2$ concentration and the atmospheric corrosion rate of weathering steel. However, this does not mean that the $NO_2$ concentration did not affect the atmospheric corrosion of weathering steel.

Fig. 8 reveals the relationship between the average

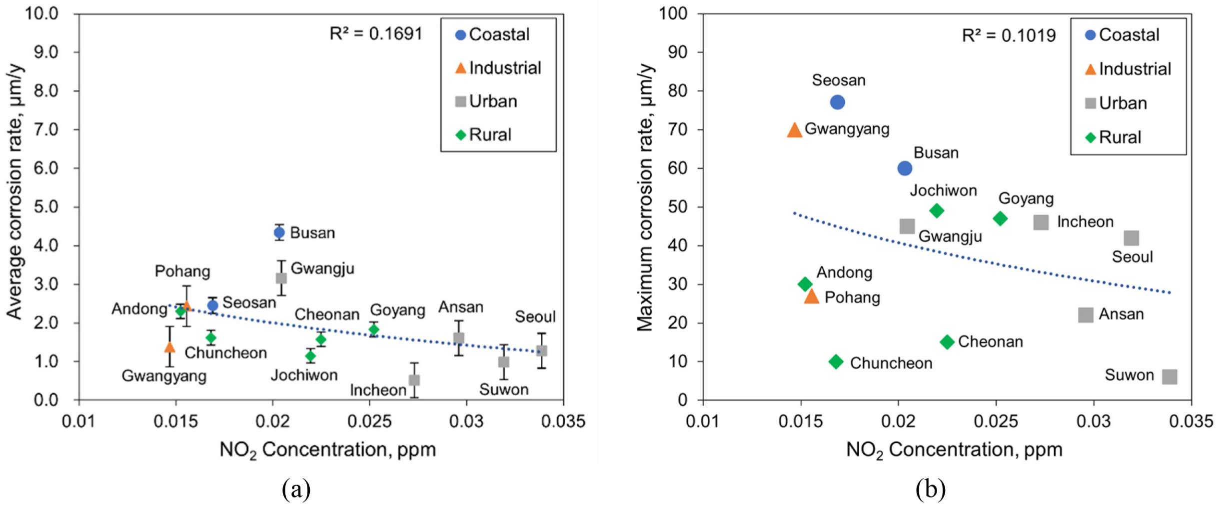


**Fig. 7. Relationship between $NO_2$ concentration and the atmospheric corrosion rate of weathering steel exposed for 10 years in Korea: (a) Average corrosion rate, and (b) Maximum corrosion rate**

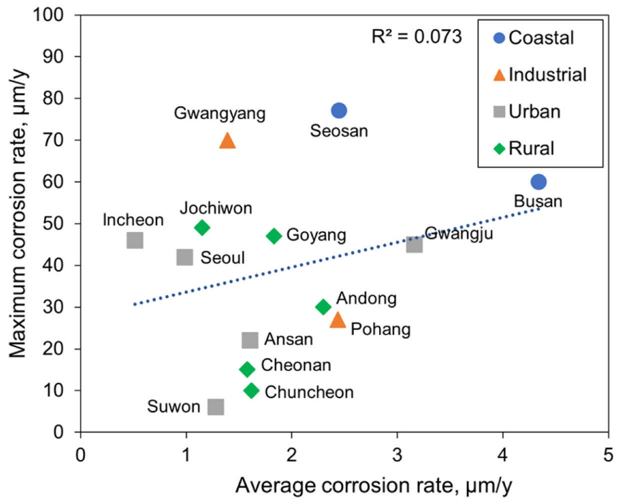


**Fig. 8. Relationship between the average corrosion rate and the maximum corrosion rate obtained from the outdoor exposure test for 10 years in Korea**

corrosion rate and the maximum corrosion rate of weathering steel obtained from the outdoor exposure test for 10 years in Korea. The trend equation between the maximum corrosion rate and the average corrosion rate was $y = 5.9714x + 27.638$. That is, the maximum corrosion rate was about 6.0 times larger than the average corrosion rate, and this means that weathering steel may be corroded irregularly even with totally uniform exposure to corrosion. However, it should be noted that the maximum corrosion rate of carbon steel was about 7.3 times greater than the average corrosion rate of carbon steel [10].

### 3.3 Surface appearance of weathering steel according to the outdoor exposure test

Fig. 9 shows the effect of exposure time on the surface appearance of weathering steel according to the outdoor exposure test in four typical sites: a coastal area (Seosan), an industrial area (Gwangyang), an urban area (Seoul), and a rural area (Andong). As the exposure time increases, the appearance of weathering steel changes to red color, and after 1.5 years, the color of the steel changes from red to black tone.

Fig. 10 shows the relationship between the average corrosion rate and the color difference of weathering steel exposed to the outdoors for 10 years in Korea. The red dashed line in the figure indicates a color difference before the test. Regardless of the exposure sites, the color differences were increased. Note that there was no relationship between the corrosion rate of weathering steel and the color difference.

Fig. 11 shows the relationship between the blackening index ($\Delta L^*$) of weathering steel for 10 years exposed to the outdoors in Korea, and the (a) corrosion rate, (b) distance from the coast, (c) time of wetness, (d) $SO_2$ concentration, and (e) $NO_2$ concentration. The red dashed line in the figures indicates the blackening index before the test. With increases in the corrosion rate and the time of wetness, the blackening index increased slightly, but the other factors including the distance from the coast and concentrations of $SO_2$ and $NO_2$, did not

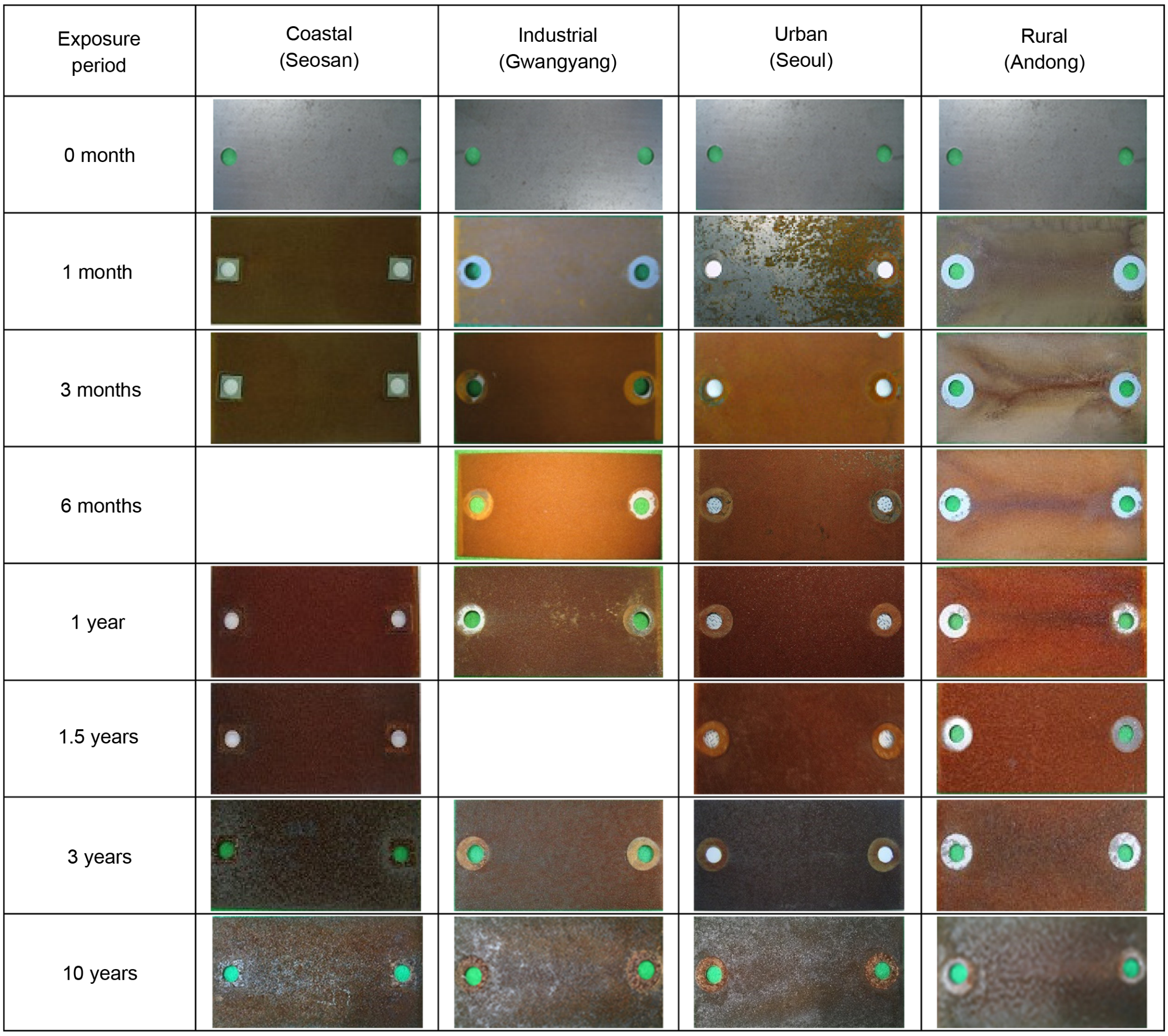


**Fig. 9. Effect of exposure time on the surface appearance of weathering steel by outdoor exposure test in four typical sites**

affect the index.

Fig. 12 reveals the relationship between the redness index (Δa*) of weathering steel for 10 years exposed to the outdoors in Korea and the (a) corrosion rate, (b) distance from the coast, (c) time of wetness, (d) $SO_2$ concentration, and (e) $NO_2$ concentration. The red dashed line in the figure indicates the redness index before the test. With increasing the corrosion rate and the time of wetness, the redness index increased slightly, but the other factors, including the distance from the coast and concentrations of $SO_2$ and $NO_2$, did not affect the index.

Fig. 13 shows the relationship between the yellowing index (Δb*) of weathering steel for 10 years exposed to the outdoors in Korea, and the (a) corrosion rate, (b)

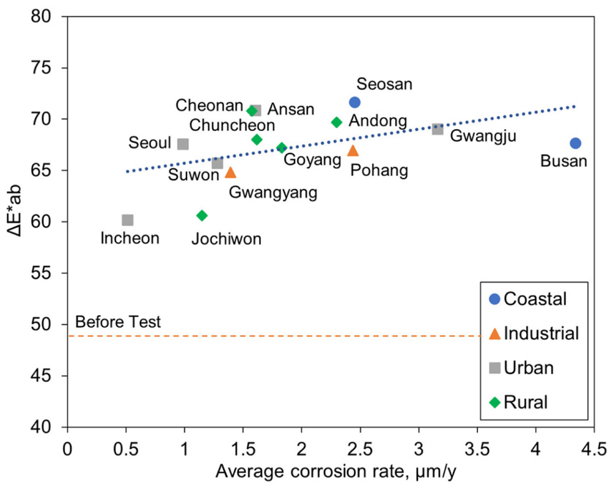


**Fig. 10. Relationship between the average corrosion rate and the color difference of weathering steel exposed to the outdoors for 10 years in Korea**

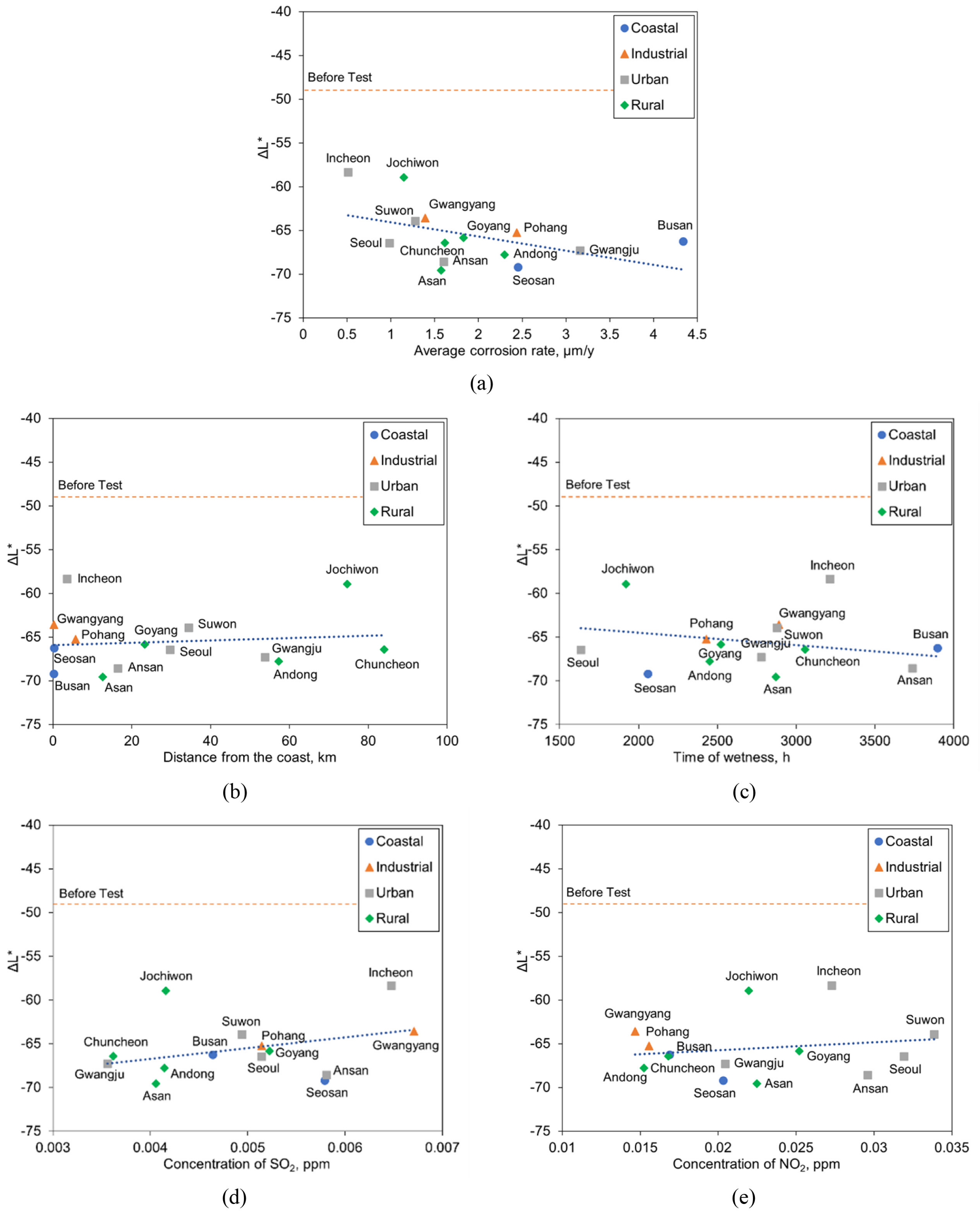


**Fig. 11. Relationship between the blackening index (ΔL*) of weathering steel for 10 years exposed to the outdoors in Korea and the (a) corrosion rate, (b) distance from the coast, (c) time of wetness, (d) $SO_2$ concentration, and (e) $NO_2$ concentration**

distance from the coast, (c) time of wetness, (d) $SO_2$ concentration, and (e) $NO_2$ concentration. The red dashed line in the figure indicates the yellowing index before the test. With increasing the corrosion rate and the time of wetness, the yellowing index increased slightly, but the other factors including the distance from

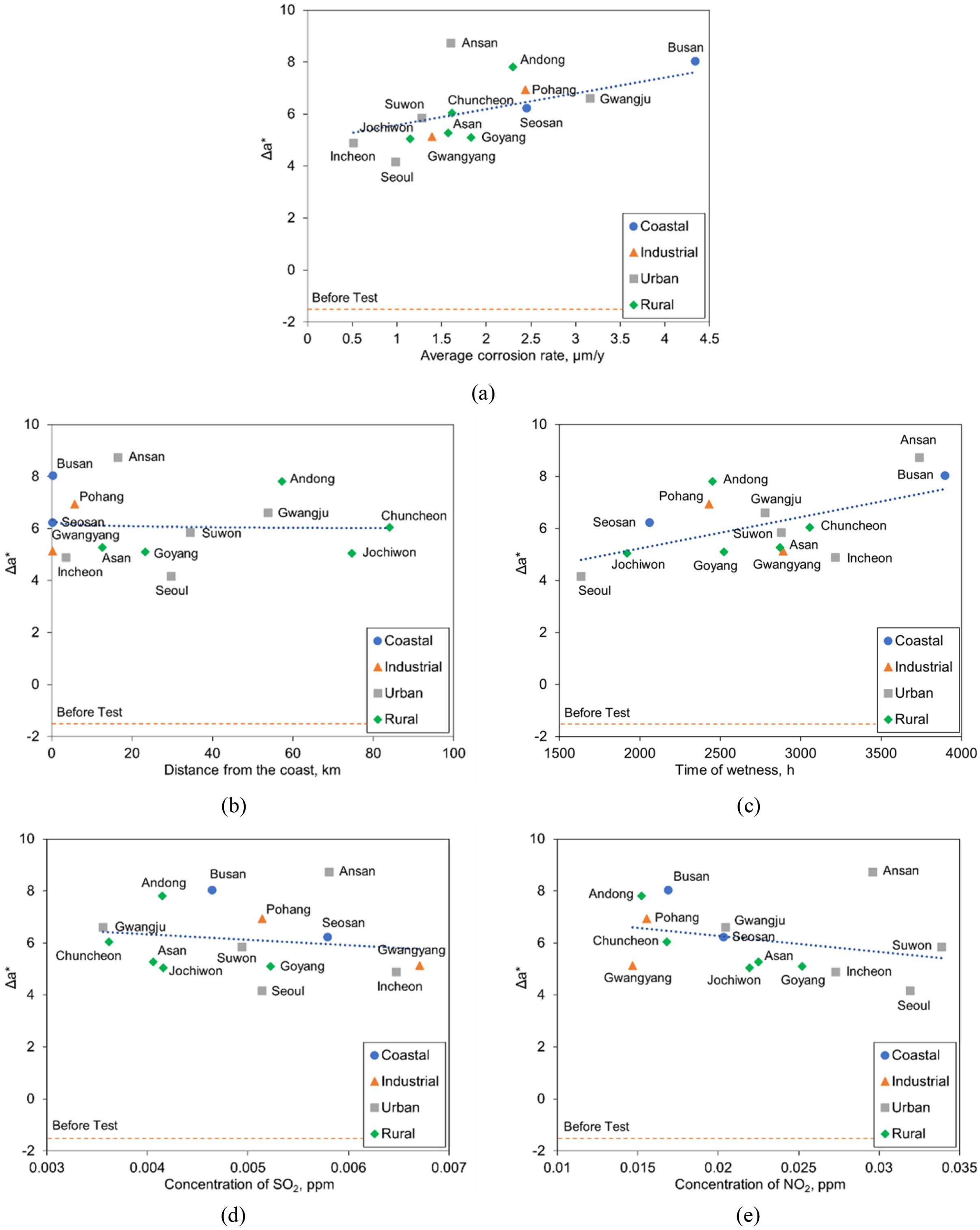


**Fig. 12. Relationship between the redness index (Δa*) of weathering steel for 10 years exposed to the outdoors in Korea and the (a) corrosion rate, (b) distance from the coast, (c) time of wetness, (d) $SO_2$ concentration, and (e) $NO_2$ concentration**

the coast, concentration of $SO_2$ and $NO_2$, did not affect the index.

Fig. 14 shows the relationship between the glossiness (ΔGloss) of weathering steel for 10 years exposed to the

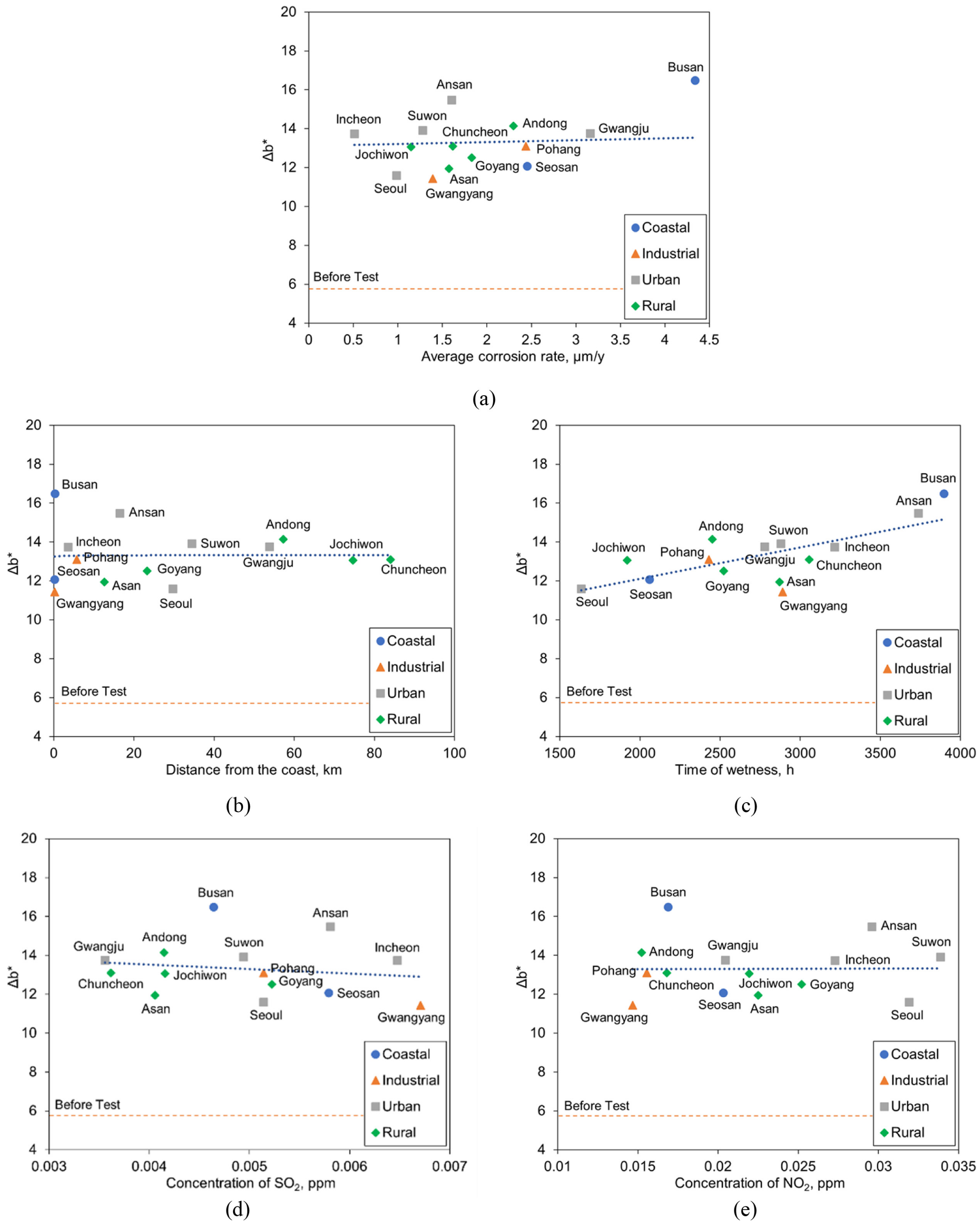


**Fig. 13. Relationship between the yellowing index (Δb*) of weathering steel for 10 years exposed to the outdoors in Korea and the (a) corrosion rate, (b) distance from the coast, (c) time of wetness, (d) $SO_2$ concentration, and (e) $NO_2$ concentration**

outdoors in Korea, and the (a) corrosion rate, (b) distance from the coast, (c) time of wetness, (d) $SO_2$ concentration, and (e) $NO_2$ concentration. The red dashed line in the figure indicates the glossiness before the test. As can be

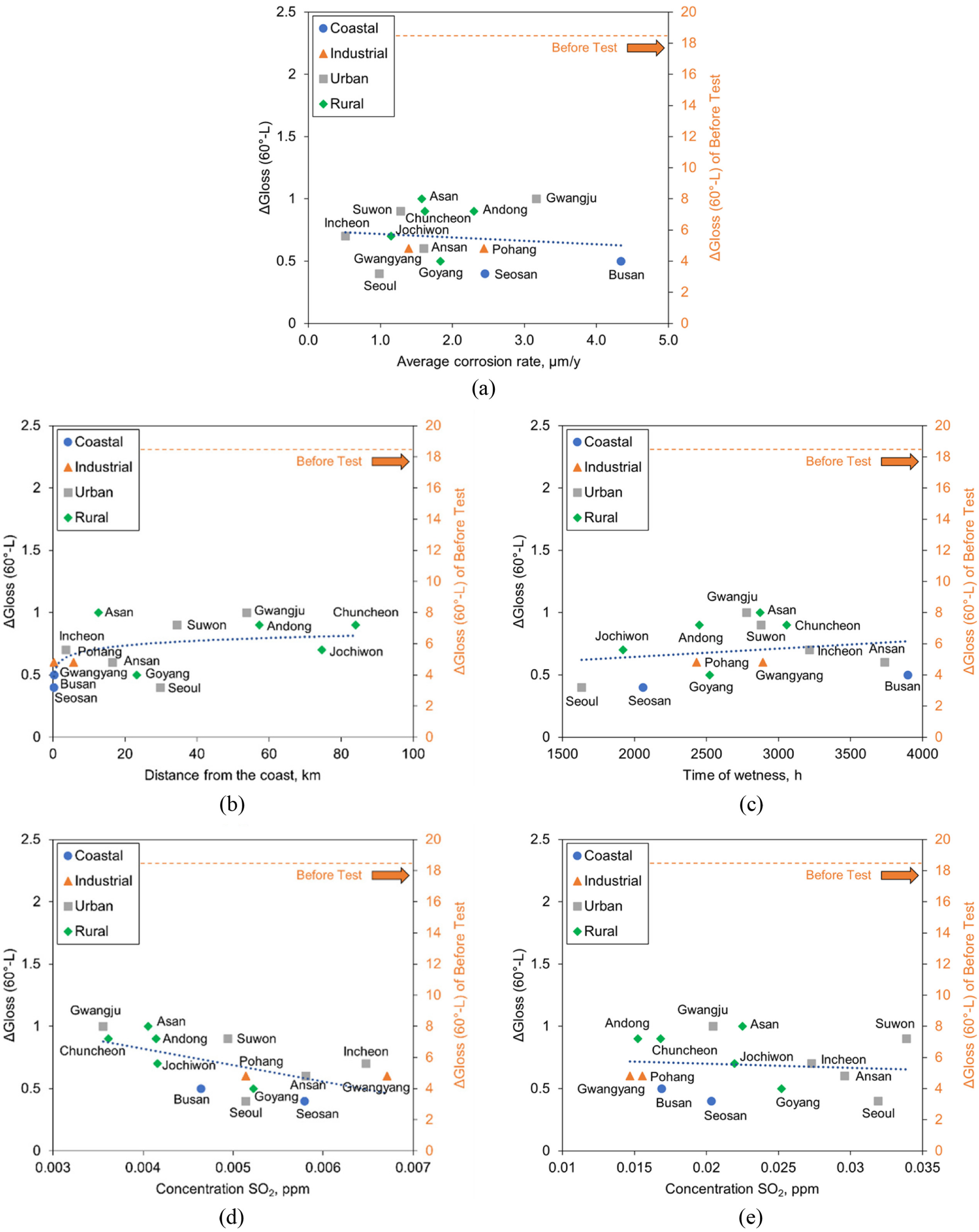


**Fig. 14. Relationship between the glossiness (ΔGross) of weathering steel for 10 years exposed to the outdoors in Korea and the (a) corrosion rate, (b) distance from the coast, (c) time of wetness, (d) $SO_2$ concentration, and (e) $NO_2$ concentration**

seen, regardless of the exposure sites, the glossiness was decreased. Note that there was no relationship between the corrosion rate and environmental factors, and the glossiness.

## 4. Conclusions

This work performed outdoor exposure tests of weathering steel for 10 years in Korea, determined the atmospheric corrosion rate, and analyzed the surface appearance. As a result, the following can be concluded:

1. The coastal areas, the average corrosion rate was obtained from (2.45 to 4.34) μm/y, and the maximum corrosion rate was determined to be from (60.0 to 77.0) μm/y. The industrial areas, the average corrosion rate in industrial area was obtained from (1.38 to 2.44) μm/y, and the maximum corrosion rate was determined to be from (27.0 to 70.0) μm/y. The urban areas the average corrosion rate was obtained from (0.51 to 3.16) μm/y, and the maximum corrosion rate was determined to be from (6.0 to 46.0) μm/y. The rural areas, the average corrosion rate was obtained from (1.15 to 2.30) μm/y, and the maximum corrosion rate was determined to be from (10.0 to 49.0) μm/y. It should be noted that the maximum corrosion rate was about 6.0 times greater than the average corrosion rate.

2. Regardless of the exposure sites, the color differences were increased. Note that there was no relationship between the corrosion rate of weathering steel and the color difference; with increasing corrosion rate and time of wetness, the blackening along with the redness and yellowing indices increased slightly, but the other factors including the distance from the coast and concentrations of $SO_2$ and $NO_2$, did not affect the indices. On the other hand, regardless of the exposure sites, the glossiness was decreased and there was no relationship between the corrosion rate and environmental factors and the glossiness.

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