Atmospheric Corrosion Behavior of Carbon Steel and Galvanized Steel after Exposure in Eretan and Ciwaringin, West Java Province, Indonesia

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Abstract: *The investigation of corrosion for carbon steel and galvanized steel has been conducted in the marine atmosphere of Eretan and Ciwaringin Districts, West Java Province. The exposure time of the field test was up to 200 days, and their corrosion rates are determined according to the weight loss method. The objective of the work is to elucidate the corrosion behavior of those alloys, which is affected by distances from the coastline and environmental conditions. The magnitude of the corrosion rate for carbon steel was 20 times as high as that for galvanized steel in both districts. The distance from coastline has significantly affected the magnitude of corrosion rate, where that both alloys in Ciwaringin are lower than that in Eretan. The deposition of chloride ion in Eretan and Ciwaringin Districts were 4.305 mg/m^2 day and 1.863 mg/m^2 day, respectively, where the higher chloride ion can tend to increase the corrosion rates. Relative humidity (RH), which is over 60%, has an essential role in the corrosion process as well as rainfall. The uniform corrosion attack was observed both alloys after exposure. The corrosion product phases of galvanized steel exhibit zincite, hydrozincite, and simonkolleite as the typical coastline atmosphere phases in Eretan, but not in Ciwaringin. The formation of rust product for both metals lead the decrease of further corrosion attack due to the barrier between metal and environment. The usage of galvanized steel is remarkable to minimize corrosion attack compared to that of carbon steel in the tropical coastline.*

Keywords: *carbon steel; galvanized steel; atmospheric corrosion; coastline; corrosion product*

■ INTRODUCTION

Carbon steel, alloyed steel, and galvanized steel are the most generally utilized metallic material in open-air structures, being used to build a variety of metallic structures due to their good mechanical strength, reasonable cost, and easy manufacture in marine and coastal environment. Atmospheric corrosion phenomena could contribute a detrimental effect significantly for various metallic constructions, where 80% of all degradations made by its corrosion in the constructions due to the atmospheric corrosion [1]. The magnitude of atmospheric corrosion depends upon the time of wetness (TOW) that the metal surface tends to become wet conditions. TOW defines the duration of the electrochemical process, which is associated with the water vapor content of the atmosphere, such as the relative humidity (RH) at a certain temperature. The presence of RH and temperature variations could lead to cyclic wet and dry periods [2], where on the wet surface of a metal, the corrosion process occurs spontaneously, comparing with the dry surface [3]. The degree of corrosion attack also depends on the length of the wet time. Furthermore, generally, the atmospheric corrosion conditions are complicated for holistic investigation, which considers the corrosion behavior of metals in the function of geographic regions, various climates, and seasons. The alteration of those functions can vary the magnitude of corrosion rates for metals. On the other hand, the other complications of atmospheric corrosion are related to the presence of several parameters, such as air temperature, relative humidity, wind speed, and wind direction, various airborne pollutants, and so on [4]. However, it is very difficult to simulate the real condition with many factors into a laboratory scale. The vulnerability of atmospheric corrosion to steel structures in the coastal environment has been reported by many researchers, where metal degradation is major concern [5-7]. In addition, the severity of atmospheric corrosion depends on the location of the environment, including inland (rural), urban, industry and marine regions, where marine region is one of the most severe locations. One of the main environmental factors is the presence of certain pollutants as airborne chloride salt in marine region [8], which mainly decreases the corrosion resistances of metals.

Furthermore, the mitigation of corrosion must be conducted to minimize the severity of metal degradation. Corrosion protection methods commonly used to alter electrochemical reaction of metals from surrounded environment in which consists of inhibitors, cathodic protection, and organic and metallic coatings [9]. Galvanized steel is one of metallic coated steel, where subtract of steel has been coated in zinc to increase corrosion resistance. Galvanized steel is applied widely in infrastructure and construction both onshore and offshore. The corrosion protection of that steel mostly depends on the porosity, thickness, and the adherence of zinc coated on steel. In preceding work, the effect of galvanized steel significantly reduces the corrosion rate up to 20 times compared to structural plain steel in Limbangan area, Indramayu, West Java, where the deleterious effect of chloride ion increases the magnitude of corrosion rate by degrading the formation of protected oxide layer without zinc coating [10]. However, with regard to atmospheric corrosion subject, there is no or little investigation on the corrosion in the Eretan and Ciwaringin Districts, as a representative of tropical regions in Indonesia, even though carbon steel and galvanized steel were investigated systemically in the other regions of West Java [10]. Therefore, the objective of the present work is to investigate and elucidate the corrosion behavior of mild steel and galvanized steel as representative of infrastructural metals in the tropical atmosphere in Eretan and Ciwaringin Districts, West Java Province, Indonesia.

■ EXPERIMENTAL SECTION

The Specimen Preparation

In this recent work, a plate shape of as-received carbon steel was employed for atmospheric corrosion specimens. This alloy was cut into 15 cm × 7.5 cm × 0.3 cm. A pickling processing was carried out in the specimen in which refers to the standard of ASTM G-1 before exposure. During the field test, the observation of corrosion behavior was only on one side of the upper specimen surface, while the bottom side was covered fully with black adhesive tape. The duration of test exposure was up to 200 days. All specimens were set up at a 45° angle from a horizontal axis and oriented to face toward to open sea. The chemical composition of the specimen is shown in Table 1 as well as the preceding work from Nuraini and co-workers [10].

Table 1. Chemical composition of specimen employed in the recent study (wt.%) [10]

Fe	Si	P	Mn	Ni	Cr	Cu	Ti	C	Zn	Al
99.00	0.11	0.02	0.29	0.01	0.30	0.01	0.01	0.13	-	-

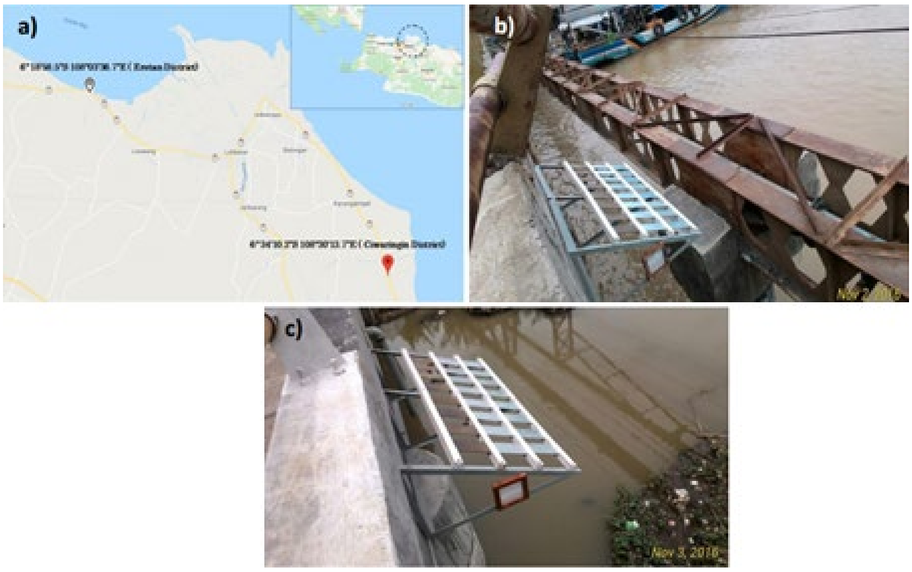

Fig 1. (a) Location of two field sites in West Java Province; test racks of atmospheric corrosion in (b) Eretan District and (c) Ciwaringin District

The Location of Field Test

The magnitude of atmospheric corrosion leads to varying in different geographic regions, where the distance of specimens to the coastal lines is the primary factor. With regards to the recent study, two exposure sites, such as Eretan and Ciwaringin District, were located in 50 m and 2000 m from the sea, respectively, as shown in Fig. 1(a). The value of chloride deposition rate was specified by a wood rectangular collector, which contains cross stitch cloth in the dimension of 10 cm × 10 cm, as shown in Fig. 1(b) and Fig. 1(c). The airborne salt, which contains chloride ion, was trapped and precipitated in that collector during exposure. The measurement of chloride ion was conducted by the HACH chloride titrator strips kit. In addition, local data of relative humidity (RH), air temperature, wind direction, and daily rainfall was officially obtained from Meteorological, Climatological and Geophysical Agency, Indonesia.

Characterization and Analysis of Corroded Specimens after Exposure

After a certain exposure time in both sites, the corroded specimens were retrieved, analyzed, and characterized in a laboratory. The procedure of cleaning and pickling processes was carried out to remove rust products which refer to the standard of ASTM G-1. The method of measurement of the corrosion rate was conducted based on weight loss. The measurements of the loss of weight of the materials are related to a function of exposure time. Moreover, the weight loss in each specimen before and after exposure was calculated using the following formula:

$$CR = \frac{\Delta W.K}{d.A.t}$$

where CR = corrosion rate in mills per year (mpy); ΔW = weight loss in grams; K= constant; d = metal density in g/cm^3; t = exposure time (day). The morphology of the surface of corroded materials, the distribution of elemental composition for rust products, and various phases of corrosion products were observed and identified by Scanning Electron Microscopy (SEM), Energy Dispersive Spectroscopy (EDS), and X-Ray Diffraction (XRD) respectively.

■ RESULTS AND DISCUSSION

Corrosion Rates of Metals

Fig. 2 shows the corrosion rate of carbon steel as a function of exposure time in Eretan and Ciwaringin District, West Java Province, Indonesia. The corrosion rates for these materials tend to increase and decrease up to final exposure time initially. It was found that the magnitude of the corrosion rate for carbon steel in the

Eretan region becomes higher than that in the Ciwaringin region. Moreover, Fig. 3 also shows the corrosion rate of galvanized steel as a function of exposure time in Eretan District and Ciwaringin District, West Java Province, Indonesia. The magnitude of the corrosion rate of galvanized steel in the Ciwaringin region initially was higher than that in the Eretan region. After 142 days of exposure, the opposite of its behavior took place up to 200 days.

On the basis of the result, the magnitude of corrosion rates for carbon steel is 20 times higher than those for galvanized steels in both regions of a field test. The major factor of distance from coastline to test site affects the corrosion rate of metals, where the closer test site from the coast line could increase the corrosion attack on metals [11]. In present work, the corrosion rate of exposed carbon steel at a test station near the sea shore line has the highest corrosion rate at the Eretan region, but not at the Ciwaringin region. The same behavior of distance factor is also the same on galvanized steel.

On the other hand, the corrosion resistance of galvanized steel is not only considered from the distance factor but also the thickness of zinc coating on subtract. The increase in thickness of zinc coating could enhance the corrosion resistance of galvanized steel [12]. The average thickness of as-received galvanized steel is around 55 μm (2.2 mils). In tropical environment, the prediction of service life of galvanized steel, which defined to be occurred 5% red rusting of the steel surface, is estimated 25 years [13]. In a recent study, the estimated service life of galvanized steel in Eretan and Ciwaringin Districts is 21 and 35 years, respectively. However, the difference in the service life of this investigated atmospheric corrosion subject may take place due to the complexity of environmental factors. Prifiharni and co-workers reported the role of distance from sea line to site test in Limbangan and Karangsong region, where the magnitude of atmospheric corrosion rate of carbon steel and galvanized steel raise in getting closer from sea line [14]. Therefore, it implies that the service of life of galvanized steel increase in increasing the distance from the sea coastline to the metal structures. In addition, the estimated service life of carbon steel in the Ciwaringin District is also longer than that in the Eretan District.

The susceptibility of atmospheric corrosion of metal structure is related to the duration of exposure time and essential climatic variables such as air temperature (T), relative humidity (RH), airborne salinity, and sulfur content [6]. The other factors that may be considered are wind direction and precipitation. The electrochemical process initiates on the surface of a metal to corrode gradually at a critical level humidity (RH_{crit}) of 60% [5], then the corrosion rate increases

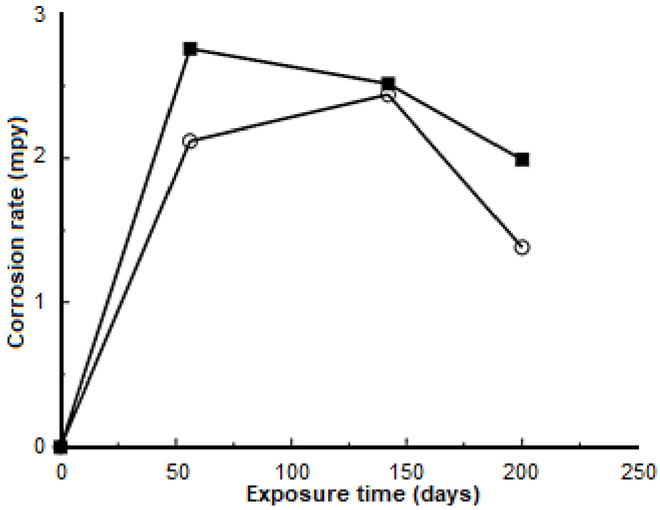

Fig 2. Corrosion rate of carbon steel as function of exposure time in ▪ Eretan region and ○ Ciwaringin region, West Java Province, Indonesia

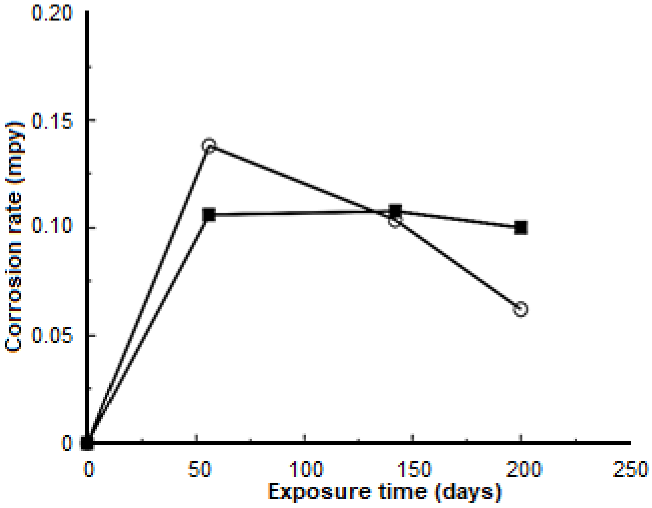

Fig 3. Corrosion rate of galvanized steel as a function of exposure time in ▪ Eretan region and ○ Ciwaringin region, West Java Province, Indonesia

drastically at 80% RH [15]. The existence of a thin electrolyte layer spreads on the metallic surface takes place when reached to RH_{crit} [8].

Fig. 4 shows a representative relative humidity (RH) variation as a function of time exposure at Eretan and Ciwaringin Districts, which was retrieved and carried out a subsequent data processing from a raw database of Meteorological, Climatological and Geophysical Agency, Indonesia [16]. Based on the current result, it was more than 80% of the percentage from all-time exposure, which is categorized as average daily RH_{crit}. The highest of RH tends to initiate the electrochemical process on the surface of a metal, which allows a longer time of wetness (TOW). TOW is defined as the time during wetness (condensation process) that took place on the exposed surface to the environment when RH is greater than 80% at a temperature greater than 0 °C [5]. In addition, both Ciwaringin and Eretan Districts are located in tropical regions, which have warm temperatures, ranges from 23 to 33 °C during field tests [16]. On the other hand, the condensation of humidity is regarded as a major cause of corrosion attack of metal and alloys, which depends on RH and the alteration of air temperature. Based on the results of corrosion rates in Fig. 2 and 3, the effect of high RH, which tends to increase corrosion attack, has no or little impact on galvanized steel due to low corrosion rate, but not on carbon steel.

Fig. 5 shows daily rainfall as a function of time exposures at Eretan and Ciwaringin Districts, West Java Province, which was retrieved and carried out a subsequent data processing from a raw database of Meteorological, Climatological and Geophysical Agency, Indonesia [16]. The daily rainfall frequently occurs in all exposure time, where the highest peak of rainfall was in 30 days of exposure or the beginning of the first month of the year. Condensation (dew) could not wash the surface of the metal, so the precipitated pollutant (chloride content) on it increases and could be more severe than

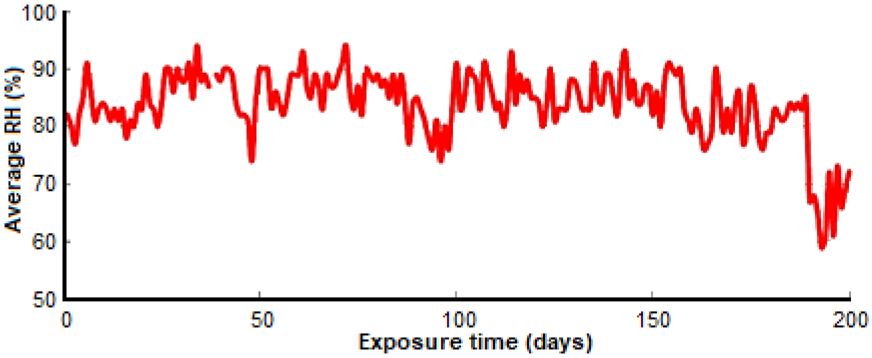

Fig 4. A representative relative humidity (RH) variation as a function of exposure time at Eretan and Ciwaringin Districts, West Java province

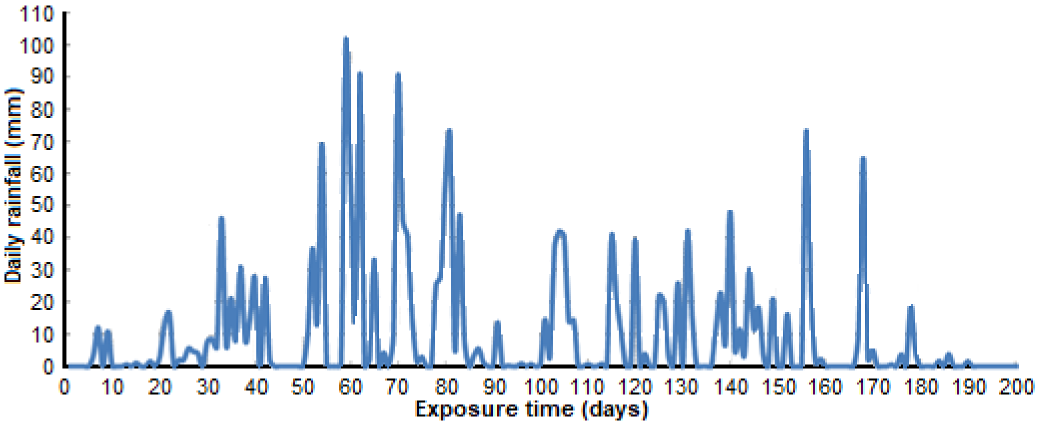

Fig 5. Daily rainfall as a function of exposure time at Eretan and Ciwaringin Districts, West Java province

rain. However, high intensity of duration of rainfall could lead to washing away the contaminant of pollutants on the surface of the metal. In addition, rainfall also contributes to increasing the formation of a thick layer of water and also absorbs corrosion agents such as H^+ and SO_4^{2-} [17] but depending on the duration of daily dry sessions and types of pollutant in a different environment. Therefore, it is difficult to elucidate only the role of precipitation towards the corrosion rates of both alloys. The presence of chloride in airborne salt is predominantly to take responsibility to increase the severity of corrosion attack compared to the presence of other corrosion agents such as H^+ and SO_4^{2-} in the marine environment.

Airborne salinity refers to the content of suspended salt in the atmosphere, which is predominantly chloride ion in the coastal region. The airborne salt that contains chloride ion was dissolved in a thin electrolyte layer on the metallic surface during the condensation process, where the conductivity of it increases significantly. The higher conductivity of electrolytes could contribute to accelerating the corrosion process of metals [18-19]. In current work, the airborne salinity level was represented by the deposition rate of chloride refers to International Standard Organization (ISO) 9223:2012 [20]. On the basis of results, the deposition of chloride rate values in Eretan and Ciwaringin Districts were 4.305 mg/m^2.day and 1.863 mg/m^2.day, respectively, which are classified into S1 for the coastal region (Eretan) and S0 for Non-Coastal (Ciwaringin). It was assumed that there are no variables influencing the transport inland of airborne sea salt such as wind velocity and local topography. The distance factor of the field test site to the sea and wind direction was also considered to the magnitude of atmospheric corrosion. In addition, according to raw database service of Meteorological, Climatological and Geophysical Agency, Indonesia for wind direction [16], it is more than 51% of wind direction toward to north side. It implies that airborne salt contaminant prefers to flow to sea than to inland. The deposition of chloride rate was 117 mg/m^2.day in Limbangan District, Northern West Java at 100 meters from coastline [10], but its less rate in the Eretan District. However, the magnitude of corrosion rates for carbon steel and galvanized steel in Eretan are lower than those in Limbangan. Based on results, the lower corrosion rate in Eretan District may be caused by wind direction toward the north side, the higher intensity of rainfall, and lower airborne salinity during the exposure of field tests. Therefore, the less magnitude of corrosion rate in the Ciwaringin District comparing with that in Eretan is caused by the difference of distance from the sea.

Fig. 6 shows the highest and lowest air temperatures as a function of time exposure, which was obtained and conducted a subsequent data processing from a raw database of Meteorological, Climatological and Geophysical Agency, Indonesia [16]. The lowest air temperature occurs at night, increasing in the morning, and then raising drastically after midday. This condition took place if there is no high intensity of rainfall. The possibility of fluctuated temperature magnitude is related to solar radiation in which contributes to the corrosion rate of metals due to the semiconducting behavior of the oxidative corrosion processes [21].

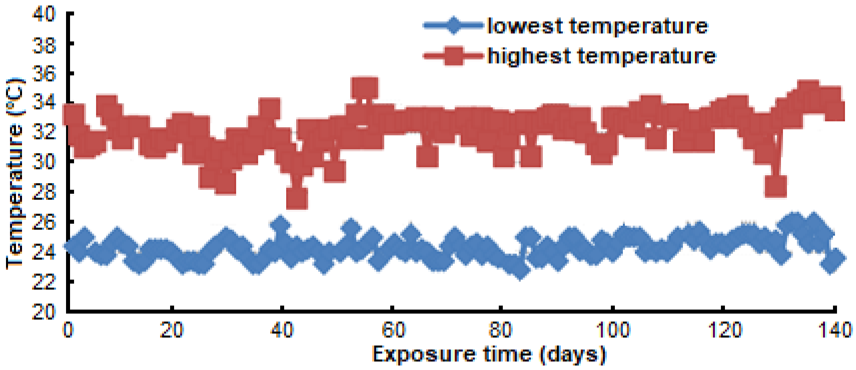

Fig 6. The highest air temperature and the lowest air temperature as function of exposure time during test

Morphology of Corroded Metals after Exposure

Fig. 7 shows macro surface appearances before exposure and after exposure up to 142 days in both Eretan and Ciwaringin Districts. The rust products were uniformly distributed on the entire surface of specimens. The abundance of rust product is denser with increasing exposure time. It implies that in the initial stage, the higher corrosion rate of steel made the rust product on steel. On the other hand, the corrosion rate decreases when a dense, thick rust product forms on the surface. Fig. 8 shows surface appearances of galvanized steel before and after exposure in both Eretan and Ciwaringin Districts up to 142 days. Before exposure, the visual results of newly galvanized steel are bright and shiny, where it has visible spangle clearly, as shown in Fig. 8(a). Within 142 days of exposure, the surface appearance of galvanized steel changes to a uniform dull gray in both Eretan and Ciwaringin Districts. The crystallization pathway of the spangle was increasingly unclear during the exposure time.

Fig. 9 shows a representative morphology of rust products for corroded steel after 200 days of exposure in Eretan and Ciwaringin Districts. On the basis of the result, the specimens were fully covered by rust products after exposure. The identification of the various types of morphologies such as grain, flakes, powdery rust particles, and easy peel-off of lamination is possible to identify after exposure in the atmosphere visually [22]. In Fig. 9(a) and 9(b), there are various shapes of rust product morphology. In Eretan, the types of rust products were cracked and flaked, which has mostly a flowery structure and cotton ball structure. In Ciwaringin, those were also the same where a cotton ball structure is predominantly. There are many flaky and cracks that lead

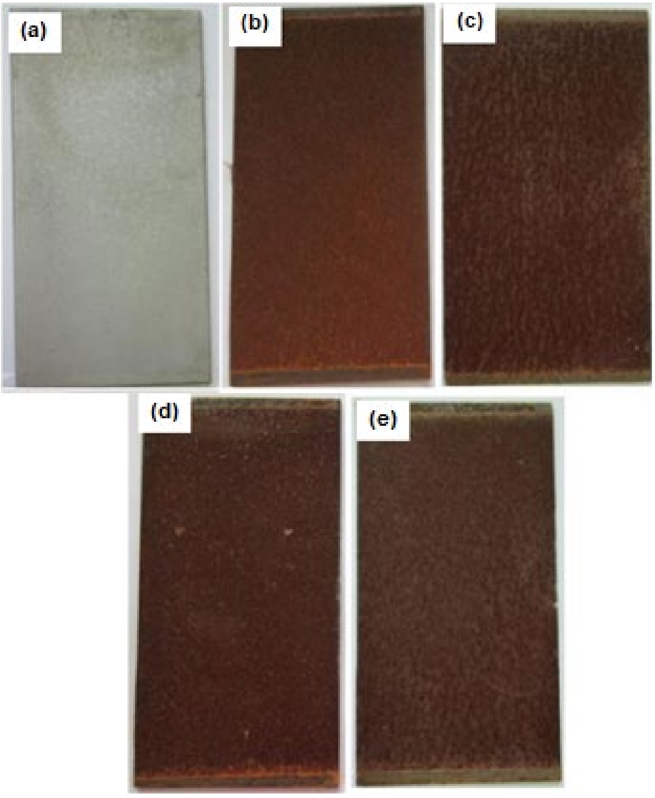

Fig 7. Photos of carbon steel (a) before exposure and after (b) 56 days of exposure and (c) 142 days exposure in Eretan; (d) 56 days of exposure and (e) 142 days exposure in Ciwaringin

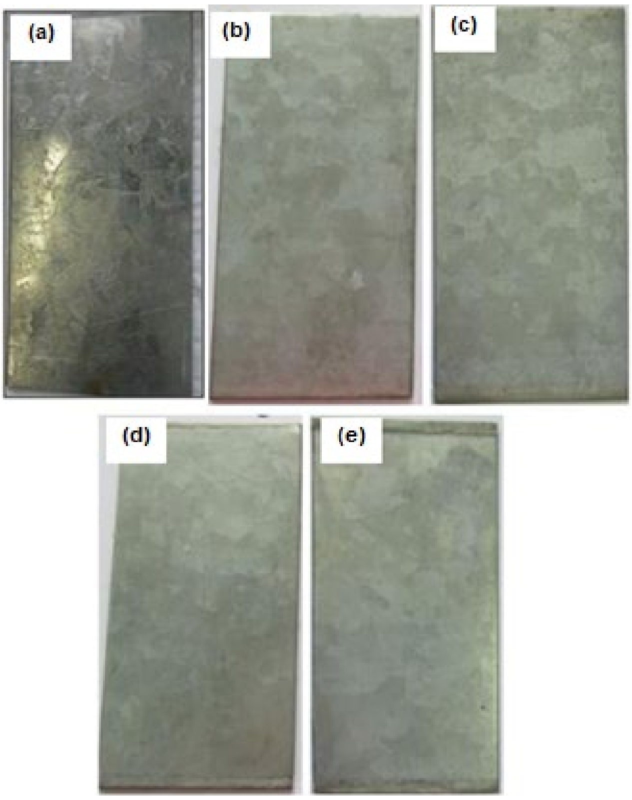

Fig 8. Photos of galvanized steel (a) before exposure and after (b) 56 days of exposure and (c) 142 days exposure in Eretan; (d) 56 days of exposure and (e) 142 days exposure in Ciwaringin

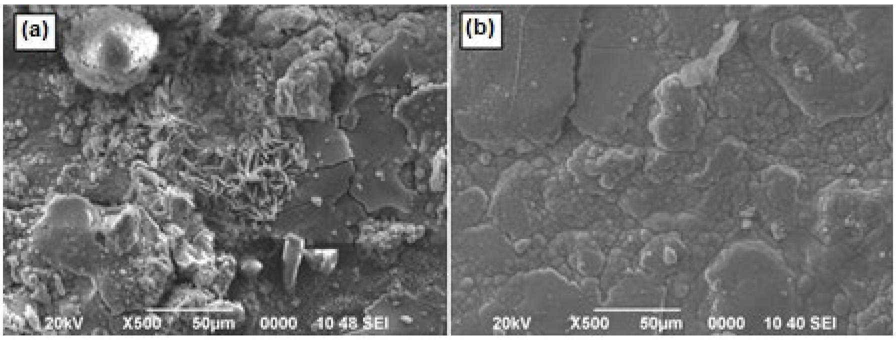

Fig 9. Representative morphology of rust product for corroded steel of exposure in (a) Eretan and (b) Ciwaringin Districts

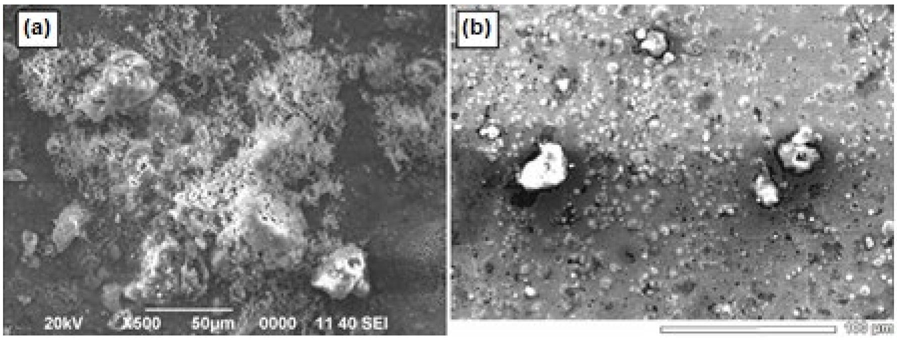

Fig 10. Representative morphology of galvanized steel after exposure in (a) Eretan and (b) Ciwaringin Districts

to the diffusion of chloride ion into the rust product from airborne salts. Morcillo and co-workers reported that the formation of coarse flakes and layered sheets on rust products in the marine atmosphere due to the presence of chloride [23] as well as the present results.

Fig. 10 shows a representative morphology of galvanized steel after 200 days of exposure in Eretan and Ciwaringin Districts. The visual observation of galvanized steel surface after exposure shows that corrosion products adhere to the metal surfaces in both districts. The morphology of the corrosion products shows deposits of granulates formed due to RH and its interaction with oxygen and the presence of a pollutant in the atmosphere, such as chloride ion [24], as shown in Fig. 10(a) and 10(b). In Fig. 10(a), certain areas on the surface were fine flake-like crystals structure observed in Eretan, where Chen and co-workers also had observed the same crystal structure as simonkolleite for galvanized steel [25]. Ciwaringin District also shows that the type of corrosion product was less dense fine cotton ball structure, as in Fig. 10(b).

Fig. 11 shows XRD of corrosion products for steel after exposure in Eretan Districts. On the basis of results, its corrosion products are identified as Magnetite (Fe_3O_4) and Lepidocrocite (γ-FeOOH). In Ciwaringin District, the corrosion products of steel surface are identified as geothite (α-FeOOH) and Lepidocrocite (γ-FeOOH), as shown in Fig. 12. Furthermore, the initial stage of the steel rusting forms ferrous hydroxide ($Fe(OH)_2$), which

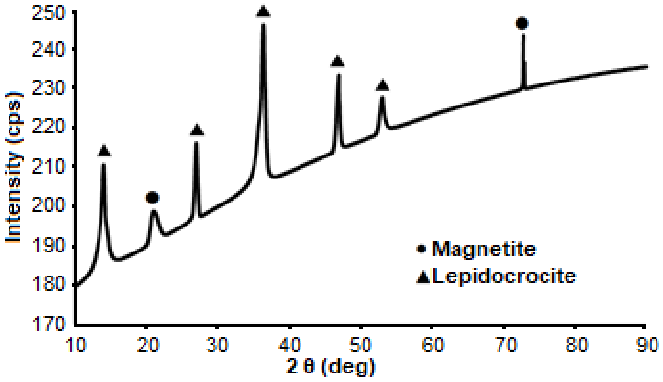

Fig 11. X-Ray Diffraction of various corrosion products for carbon steel after exposure in Eretan Districts

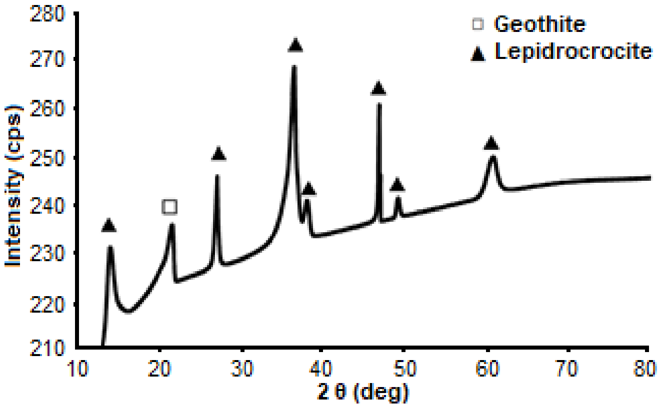

Fig 12. X-Ray Diffraction of various corrosion products for carbon steel after exposure in Ciwaringin Districts

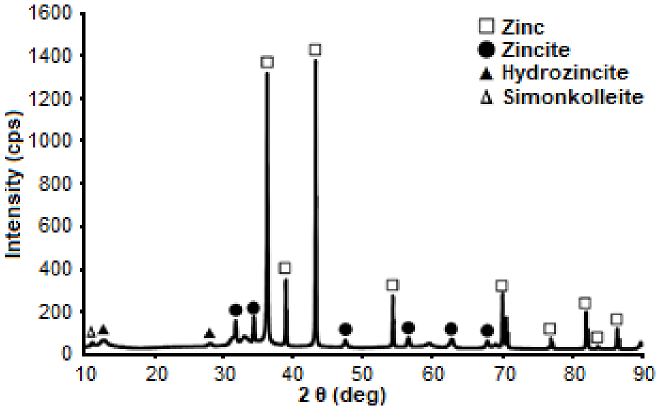

Fig 13. X-Ray Diffraction of various corrosion product for galvanized steel after exposure in Eretan Districts

oxidizes to lepidocrocite (γ-FeOOH). The formation of magnetite (Fe_3O_4) took place by the reduction process inside the flaked rust layer, where the diffusion of oxygen is restricted from the outside rust layer. The magnetite was formed in the presence of chloride ion by the transformation of lepidocrocite [7]. Moreover, the existence of akaganeite phase (β-FeOOH) is common as a primary phase in the severe marine environment [26]. The presence of the magnetite phase is also found in atmospheres with a lower airborne salinity [23]. However, in present work, there is no evidence of akaganeite phase, where the magnetite phase was identified. It implies that there is less severe of the marine environment due to lower airborne salinity levels (4.305 mg/m^2.day). In Ciwaringin District, the lepidocrocite phase was predominantly as major phases compared to the Geothite phase. There are no akaganeite and magnetite phases on steel due to the lowest concentration of airborne salinity (1.865 mg/m^2.day). In the previous description, the concentration of chloride ion (airborne salinity) depends on the distance from the sea line.

Generally, in marine environment corrosion product of galvanized steel consists of simonkolleite ($Zn_5(OH)_8Cl_2{\cdot}(H_2O)$), hydrozincite ($Zn_5(CO_3)_2(OH)_6$), zinc (Zn) and sodium hydroxyl-chlorosulfate ($NaZn_4Cl(OH)_6SO_4{\cdot}6H_2O$) [27]. In present results, those are identified as zinc, zincite, hydrozincite, and simonkolleite after 200 days of exposure in Eretan District, as shown in Fig. 13. Many studies reveal that the formation of simonkolleite increased by the presence of chloride ion in the atmosphere [25-27]. In thermodynamic stability, zinc metal is easy to react with oxygen, forming an oxide film (ZnO) at ambient temperature. This oxide has good adhesion and compactness, which may protect subtract of steel from corrosion process. The presence of hydrozincite is also predominantly at the marine sites [28], where the surfaces of zinc exposed to the air at the RH range of 85%–100% [25]. On the basis of results, within 200 days of exposure, there is 45% of the percentage that reach or exceed RH 85%. In addition, the presence of CO_2 gas dissolved into a thin layer of electrolytes on the surface of the metal, which leads to the formation of zinc carbonate and hydrozincite in long-term outdoor exposure with little contaminants in open air [29]. However, in the existence of chloride as a marine pollutant, zincite will subsequently react with chloride to form insoluble simonkolleite [25] as follows

$$5ZnO + 2Cl^- + 6H_2O \rightarrow Zn_5(OH)_8Cl_2 \cdot H_2O + 2OH^-$$

In Ciwaringin District, the distance of the site from the coastline is around 2000 meters, which the airborne salinity level decreases. In this location, the XRD result shows phases of galvanized steel as Zinc and zinc chloride ($ZnCl_2$), as shown in Fig.14. However, there are no zincite, simonkolleite, and hydrozincite phases. It presumes that the XRD apparatus was difficult to detect those phases due to the less amount of the products. In the initial stage of exposure, the magnitude of corrosion rate in Ciwaringin is higher than that in Eretan, in which is possible to be caused by no those protective phases on the

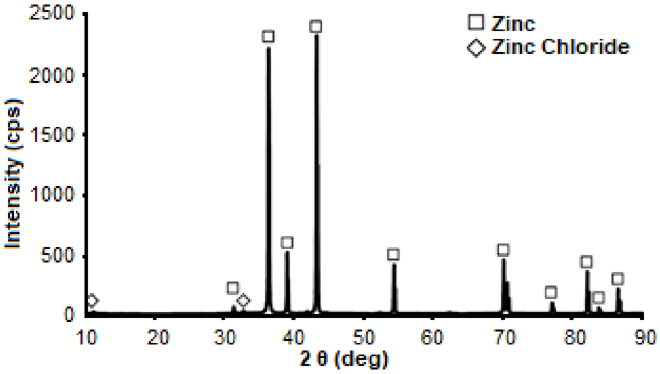

Fig 14. X-Ray Diffraction of various corrosion product for galvanized steel after exposure in Ciwaringin Districts

Table 2. The elemental semi-quantitative composition of corrosion product on steel after exposure

Element	Mass %	
	Ciwaringin District	Eretan District
O	18.75	19.22
S	0.14	0.29
Cl	0.05	0.49
Fe	81.06	80.01

Table 3. The elemental semi-quantitative composition of corrosion product on galvanized steel after exposure

Element	Mass %	
	Ciwaringin District	Eretan District
O	5.12	14.36
Si	0.06	0.90
S	0.20	0.37
Cl	0.04	0.90
Ca	0.01	0.59
Fe	0.41	0.32
Zn	98.18	82.56

surface of galvanized steel. Furthermore, without those protective corrosion products, it could be elucidated by the fact that the chloride ion directly reacts with metallic zinc to form soluble zinc chloride, which would offer no protection from the marine environment [25]. Zinc chloride can be physically removed from the surface of galvanized steel or dissolved by rain or condensation [27] during exposure over RH 85%. Furthermore, there is the fact that the lower magnitude of corrosion rate in Ciwaringin District took place after occurrence of the initial stage. However, it could not be explained by the presence of recent salt products on the metal surface. On the other hand, the alteration of surface appearance from shiny to dull could be considered to be the indication for the form of zincite and hydrozincite phases on the metal surface during exposure.

Table 2 shows the major elements in the semi-quantitative composition of steel after exposure. On the basis of results, the elemental concentration of both Cl and O in Eretan District is higher than those in Ciwaringin District, which related to the formation of corrosion products. Table 3 also shows the principal elements in the semi-quantitative composition of galvanized steel after exposure, which the concentration of both Cl and O in Eretan District is higher compared to those in Ciwaringin. Furthermore, the main role of chloride ion has been already described in previous section, where the magnitude of corrosion rates of both metals was higher with the closeness to the coastline. In addition, the effect of environmental parameters such as RH, rainfall, and air temperature could vary the severe behavior of corrosion each metal.

■ CONCLUSION

The magnitude of corrosion rate for steel was much higher than that for galvanized steel in both Eretan and Ciwaringin Districts due to no protection of zinc coating on the surface of the steel. The distance from coastline has a significant impact on the magnitude of corrosion rate, where both metals in Ciwaringin are lower than that in Eretan because of the presence of chloride ion. The high relative humidity and the intensity of rainfall also contribute to the severity of corrosion rates. A uniform corrosion attack was observed for both metals during exposure. The morphology of phases found in the corrosion product of steel in both districts is predominantly of lepidocrocite (γ-FeOOH). In Eretan, the typical phase from the marine environment was also found as magnetite (Fe_3O_4), but it was found as goethite (α-FeOOH) in Ciwaringin. The corrosion products of galvanized steel are identified as zincite, hydrozincite, and simonkolleite in Eretan, which are the characteristic of coastline atmosphere phases, but not in Ciwaringin. The formation of rust products for both metals can lead to a decrease of further corrosion attacks due to the barrier between the metal and corrosive environments. The galvanized steel is outstanding to mitigate the severity of atmospheric corrosion compared to that of carbon steel.

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