Results of studying atmospheric corrosion in Vietnam 1995–2005

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Abstract

Vietnam is situated in the wet tropical zone; thus, atmospheric conditions are characterized by high temperatures and a long time of wetness (TOW). In addition, the salt air coming in from the sea causes a high chloride concentration in coastal areas. Furthermore, Vietnam is a developing country, which means that air pollution is increasing with the development of industry. These factors result in significant damage to materials by atmospheric corrosion. In this report, the results of a recent study on the corrosion of carbon steel and zinc-galvanized steel at 6–8 testing sites in Vietnam over 10 recent years (1995–2005) are focused on as well as the effects of environmental factors on atmospheric corrosion. The results showed that the corrosion of carbon steel is dominated by TOW, whereas zinc-galvanized-steel corrosion strongly depends on the chloride ion concentration in the air. The corrosion losses of both carbon- and zinc-galvanized steel fit the power model well with high correlation coefficients. In addition, the characteristics of the Vietnamese climate are introduced in the form of distribution maps of temperature (T), relative humidity (RH), total rainfall and TOW. A relationship between TOW, T and RH was found that enabled the calculation of TOW from T and RH data, which are available at meteorological stations. Finally, atmospheric corrosivity is determined on the basis of data on TOW, Cl\(^-\) and SO\(_2\) concentrations, and the carbon steel corrosion rate. It is shown that in Vietnam, TOW is so long that the corrosion rate of carbon steel is in the C\(_3\) category; nevertheless, Cl\(^-\) and SO\(_2\) concentrations in the atmosphere are not high.

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Keywords: Vietnam; Atmospheric corrosion; Carbon steel; Zinc-galvanized steel; Time of wetness; Relative humidity; Total rainfall; Temperature; Cl\(^-\) concentration; SO\(_2\) concentration

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1. Introduction

Vietnam is situated in the wet tropical zone (latitude from 8°35 to 23°10N) and has a long coastline of 3200 km; thus, atmospheric conditions are characterized by high temperatures and a long time of wetness (TOW). In addition, the salt air coming in from the sea causes a high chloride concentration in coastal areas. Vietnam is also a developing country, which means that air pollution is increasing with the development of industry. These factors result in significant damage to materials exposed to the atmosphere.

The study of atmospheric corrosion in Vietnam started in the 1960s, but the results were very limited due to difficulties during the war. During 1977–1982, investigations were performed more systematically and focused on the field exposure of various materials (carbon steel, zinc-electroplated coatings and cadmium-electroplated coatings) at 8 test sites around the country. During the same period, chloride ion concentrations were determined at 15 sites by the “dry gauze” method. Other field exposure programs were carried out during 1984–1989 with cooperation from Russia. The materials exposed during this period were low-alloy steels, copper, brass, aluminum alloy and various types of organic paint. The results of the above studies were summarized in Ref. [1].

In this report, the results of a recent study on corrosion over 10 years are presented. These results focus on the corrosion of carbon steel and zinc-galvanized steel at 6–8 test sites around Vietnam and the effects of environmental factors on atmospheric corrosion. The environmental characteristics and corrosivity categories in Vietnam are also discussed.

2. Corrosion of carbon steel and galvanized steel in Vietnam

Zinc coatings have been used worldwide for many years to protect steel from corrosion because of their high resistance and relatively low price. In recent years, zinc-galvanized coatings have been extensively applied to control steel corrosion in Vietnam, and the study of the exposure of zinc-galvanized steel to the atmosphere started in 1995. At the same time, carbon steel corrosion and environmental factors were also monitored.

Test panels of size 150 × 100 × 3 mm were exposed on a rack at 45° to the horizontal facing the sea. Specimens were removed after 6 and 9 months, and after 1, 2, 3, 4 and 5 years of exposure. The corrosion products were removed by chemical cleaning in accordance with ISO 8407 [2]. Corrosion rates were determined from the weight losses of specimens in accordance with ISO 9226/1992 [3]. The test sites were located around the country and included urban and coastal areas. The positions of the test sites are shown in Fig. 1.

Environmental data (Table 1) were collected during the time of exposure: air temperature (T), relative humidity (RH) and total rainfall were obtained from the meteorological stations located at or near the test sites. T and RH were also used for calculating TOW using the procedure given in ISO 9223 [4]. The chloride deposition rates were assessed by the “dry gauze” method given in GOST 9.039–1974 ECZKC [5]. The sulfur dioxide deposition rates were determined using alkaline surfaces in accordance with ISO 9225 [6].

In general, the corrosion rates of carbon steel and zinc-galvanized steel decrease with exposure time due to the formation of corrosion products on the surface with greater protectivity. It is clear that the corrosion rate of carbon steel strongly depends on TOW, total rainfall and Cl⁻ ion concentration (Table 1 and Fig. 2) and the corrosion rate decreases in the order: Doson > Nhatrang > Danang > Hanoi > Ho Chi Minh City > Vungtau (Fig. 2).

In contrast to carbon steel, the corrosion of zinc-galvanized steel appears to be predominantly determined by the chloride ion concentration in the air. The corrosion rate is greatest in coastal areas such as Doson and Nhatrang, where the Cl⁻ concentrations are highest; it has a medium value in Danang and Vungtau with lower Cl⁻ concentrations and is lowest in Hanoi and Ho Chi Minh City, which have insignificant concentrations of chloride ions (Table 1 and Fig. 3).

Many authors [7–9] have found that the atmospheric corrosion process obeys a power model of the form $M = At^n$, where $M$ is the loss of metal, $t$ is the time of
exposure, and $A$ and $n$ are constants that depend on the environmental characteristics and the physicochemical behavior of the layers of corrosion products, respectively. The data obtained after 5 years of exposure (Figs. 4 and 5) showed that in Vietnam, the corrosion losses of both carbon and galvanized steel fitted the power model well with a high correlation ($R$). The values of $A$, $n$ and $R^2$ are given in Table 2.
3. Characteristics of climate and atmospheric corrosivity in Vietnam

3.1. Characteristics of climate

Vietnam is located in the monsoon tropical zone with one side facing the sea. It extends through 15° of latitude; thus, the climate is strongly influenced by the monsoon and the sea with a significant difference in climatic conditions from north to south.

In general, Vietnam has a high temperature throughout the year that increases gradually with decreasing latitude. There are 4 seasons in the north, where the average temperature is considerably different between winter and summer (about 17–30 °C). Meanwhile, in the south there are only 2 seasons, a dry and a wet (rainy) season with temperatures of 25–30 °C. In the central part, the temperature varies from 22 to 30 °C. Vietnam is a narrow country with more than 3200 km of coastline; thus, the sea strongly affects the climate and causes high RH throughout the country. The annual average RH is about 78–87% and varies between regions. In contrast to RH, TOW is longer in the south than in the north and increases with altitude; in the mountains RH is always 85–87%.

The total rainfall is high due to the influence of the monsoon. In general, the average rainfall is about 1000–3000 mm/year. However, there are some areas with total rainfall of 5000 mm/year (Bach Ma and Bac Quang) or <1000 mm/year (Phan Rang and Phan Thiet). The distribution of rainfall is complicated and depends on topography. The rainy season depends on the region. In the north it extends from May to October, in the south it is from May to November and in the central part it is from September to December.

The above factors cause the long TOW throughout the country; it is about 4000–6000 h/year, which is equivalent to approximately 45–75% of the year. Similarly to RH, TOW generally decreases from the north to the south; TOW is longest in the northern areas, and is about 6000 h/year. In the central part it is 5500–5700 h/year, except around Phan Rang and Phan Thiet, where TOW is <4000 h/year because of the low rainfall there. In the south it is 4000–5500 h/year, whereas in the far south of Vietnam (Camau peninsula) TOW is longer than that in the other southern regions, it is >5500 h/year.

In order to calculate TOW values, a formula for TOW in terms of T and RH was constructed from the linear regression of data obtained during 10 years at more than 100 meteorological stations.

\[ \text{TOW} = -13,050.6 - 14.087 T + 228.631 \text{RH}. \]

This equation has a high correlation coefficient \( R^2 = 0.93 \) and can be used to calculate TOW from T and RH, which are always available at meteorological stations.

3.2. Classification of atmospheric corrosivity

An exposure test program was also carried out in 2003–2004 to classify atmospheric corrosivity based on

### Table 2

| Test sites      | Carbon steel A | Carbon steel n | Carbon steel \( R^2 \) | Galvanized steel A | Galvanized steel n | Galvanized steel \( R^2 \) |
|-----------------|----------------|----------------|-------------------------|---------------------|---------------------|-------------------------|
| Hanoi           | 247.88         | 0.57           | 0.96                    | 10.54               | 0.746               | 0.99                    |
| Do son          | 295.65         | 0.700          | 0.98                    | 18.91               | 0.754               | 0.98                    |
| Danang          | 260.52         | 0.474          | 0.99                    | 22.07               | 0.422               | 0.99                    |
| Nhatrang        | 302.25         | 0.488          | 0.96                    | 34.26               | 0.391               | 0.93                    |
| Ho Chi Minh City| 192.62         | 0.466          | 0.99                    | 16.10               | 0.576               | 0.99                    |
| Vungtau         | 200.45         | 0.403          | 0.98                    | 21.39               | 0.487               | 0.98                    |

The total rainfall is high due to the influence of the monsoon. In general, the average rainfall is about 1000–3000 mm/year. However, there are some areas with total rainfall of 5000 mm/year (Bach Ma and Bac Quang) or <1000 mm/year (Phan Rang and Phan Thiet). The distribution of rainfall is complicated and depends on topography. The rainy season depends on the region. In the north it extends from May to October, in the south it is from May to November and in the central part it is from September to December.

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| No. | Test sites       | TOW h/year | ISO categ. | Cl⁻ (mg/m²/day) | ISO categ. | SO₂ (mg/m²/day) | ISO categ. | Carbon steel Corr. rate (µm/year) | ISO categ. |
|-----|------------------|------------|------------|-----------------|------------|-----------------|------------|----------------------------------|------------|
| 1   | Dien bien        | 5873       | TS5        | 1.16            | S₁₀        | 6.67            | P₀        | 28.04                            | C₅         |
| 2   | Viet tri         | 5937       | TS5        | 1.88            | S₁₀        | 7.92            | P₀        | 27.95                            | C₃         |
| 3   | Son tay          | 6007       | TS5        | 1.50            | S₁₀        | 2.80            | P₀        | 27.00                            | C₃         |
| 4   | Do son           | 6081       | TS5        | 17.51           | S₁₀        | 6.01            | P₀        | 35.59                            | C₃         |
| 5   | Hai duong        | 6226       | TS5        | 6.89            | S₁₀        | 7.95            | P₀        | 36.58                            | C₃         |
| 6   | Hanoi            | 4917       | T₄         | 2.24            | S₁₀        | 3.90            | P₀        | 31.77                            | C₃         |
| 7   | Thanh hoa        | 6138       | TS5        | 3.48            | S₁₀        | 2.49            | P₀        | 30.91                            | C₃         |
| 8   | Dong hoi         | 5604       | TS5        | 10.28           | S₁₀        | 0.98            | P₀        | 32.54                            | C₃         |
| 9   | Hue              | 6001       | TS5        | 1.33            | S₁₀        | 3.83            | P₀        | 31.51                            | C₃         |
| 10  | Danang           | 5701       | TS5        | 4.99            | S₁₀        | 1.34            | P₀        | 33.67                            | C₃         |
| 11  | Nhatrang         | 4877       | T₄         | 13.80           | S₁₀        | 12.63           | P₁        | 40.55                            | C₃         |
| 12  | Ho Chi Minh City | 4612       | T₄         | 4.58            | S₁          | 3.23            | P₀        | 24.24                            | C₂         |
| 13  | Vung tau         | 4400       | T₄         | 16.50           | S₁          | 26.18            | C₃        |                                   |            |
Fig. 6. Distribution of climatic parameters: temperature (T), relative humidity (RH), total rainfall and TOW.
TOW, Cl\textsuperscript{-} and SO\textsubscript{2} concentrations and on the corrosion rate for carbon steel.

Specimens of carbon steel were exposed at 13 test sites, and the corrosion rate was determined after the first year. At the same time, the chloride deposition rate was obtained by the “wet candle” method and the SO\textsubscript{2} concentration was determined by the “alkalized paper” method in accordance with ISO 9225 [6]. The results are shown in Table 3 and Figs. 6–8.

It can be seen that the TOW values are very high at every test site and throughout Vietnam; according to the ISO categories, they are equivalent to \( \tau_4 \) and \( \tau_5 \). The chloride ion concentrations at all sites are classified as \( S_0 \) and \( S_1 \); the highest values (\( > 10 \text{ mg/m}^2\text{day} \)) are found at coastal sites such as Doson, Donghoi, Nhatrang and Vungtau.

The sulfur dioxide concentrations are considered to be at a background level and are classified as \( P_0 \) at all sites except Ho Chi Minh City (\( P_1 \)).

The carbon steel corrosion rates are in the range of 24–40\( \mu \text{m/year} \), which are classified as \( C_3 \) at all sites except from Ho Chi Minh City (\( C_2 \)). The concentrations of Cl\textsuperscript{-} and SO\textsubscript{2} are not high but the corrosion rates of carbon steel are medium according to the ISO categories. This shows that the long TOW strongly affects the atmospheric corrosion of carbon steel in Vietnam.

4. Concluding remarks

1. The corrosion rate of carbon steel strongly depends on time of wetness (TOW), whereas the corrosion of zinc-
galvanized steel appears to be predominantly determined by the chloride ion concentration in the air.

2. The corrosion losses of both carbon and galvanized steel fitted the power model well with a high correlation coefficient.

3. TOW in Vietnam is very high; according to ISO classification, it is equivalent to $\tau_4$ or $\tau_5$. The category of carbon steel corrosivity is generally $C_3$ since it is $C_2$ at Ho Chi Minh City.

Some other results of accelerated tests simulating real atmospheric conditions and the characteristics of corrosion products formed on galvanized steel have also been reported in Refs. [10, 11], respectively.

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