SUMMARIZE THE RESULTS OF STUDY ON ATMOSPHERIC CORROSION IN VIETNAM

Le Thi Hong Lien

Center of Material Failure Analysis, Institute of Materials Science,

VAST, 18 Hoang Quoc Viet, Cau Giay, Hanoi

Email*: honglien@ims.vast.ac.vn*

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ABSTRACT

This paper summarizes the main results of field study on atmospheric corrosion in Vietnam since 1995 by now including corrosion of carbon steel, zinc coatings and copper. The climate characteristics and deposition rate of chloride and sulfur dioxide were determined during time of exposure. The results show that corrosion of carbon steel is mostly accelerated by the time of wetness and decreases with temperature increasing, meanwhile the corrosion of zinc coating and copper seems not to be dominated by humidity but by air salinity and the other factors such as rain regime, SO_2 content, and so on. In the coastal areas, the Cl^- content of the air has accelerated effect on corrosion of all tested materials. The long term testing data show that corrosion of tested materials develops mainly according to power law, however in some cases it follows linear or logarithm law depends on the protectiveness of corrosion product layer formed on the surface. The atmospheric corrosivity of Vietnam was classified according to ISO 9223 based on TOW, SO_2 and Cl^- content. The corrosion mapping was done preliminary for non-coastal areas. The studies in the current time and near future are also informed in the paper.

Keywords: field study, deposition rate of chloride, time of wetness, coastal areas, corrosion product.

1. INTRODUCTION

The study of atmospheric corrosion in Vietnam started in the 1960s, but the results gained before 1975 were very limited due to difficulties of the war. During the period of 1977–1982, the 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 over the country; the air salinity (chloride ion concentration) was determined at 15 sites [1]. A field exposure programs was carried out during 1984–1989 in cooperation with Russia. The materials exposed during this stage were low-alloy steels, copper, brass, aluminum alloy and various types of organic paint. Some results were presented in [2]. This paper summarizes studies on atmospheric corrosion in Vietnam which have been carrying out since 1995, the results focus on the corrosion of carbon steel (CS), zinc coatings and copper; The environmental characteristics and its effects on atmospheric corrosion are discussed; and the corrosivity of atmosphere were classified according to ISO 9223 [3].

2. THE ENVIRONMENTAL CHARACTERISTICS

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 monsoon and sea with a significant difference in climatic conditions from North to South. The climate data of more than 150 meteorological stations all over Vietnam were collected to draw the maps of climatic parameters affecting atmospheric corrosion as air temperature (T), air relative humidity (RH), total of rain fall (Rf) and time of wetness (TOW). The chloride (Cl^-) and SO_2 deposition rate were collected for classification of corrosivity of atmosphere.

1.1 Air temperature: Vietnam has a high temperature (T) throughout the year that increases gradually with decreasing latitude (Fig. 1a). There are 4 seasons in the North, where the average temperature is considerably different between winter and summer (about 17 – 30 °C), while 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.

1.2 Air relative humidity: Since Vietnam is a narrow and long country with one side faced to sea and the other side blocked by the mountain chains, the moisture coming from the sea stays in land and causes high RH at almost the whole country. The annual average RH is about 78 – 87 % and varies from site to site. In contrast to the temperature, RH is higher in the North in comparison with that in the South and increases with altitude; on the high mountains RH always reaches 85–87%. The variation of temperature is shown in figure 1b.

1.3 Rainfall: The total of rainfall in Vietnam is very great due to influence of monsoon. The average value is about 1000 – 3000 mm/year; however, there are some areas at the top of the mountain with greatest total of rainfall (as Bach Ma and Bac Quang with 5000 mm/year), while in some places (as Phan Rang and Phan Thiet) the total of rainfall is very low with only 1000 mm/year. The distribution of rainfall is complicated and depends on topography. The rainy season is different from region to region. In the North it extends from May to October, in the South - from May to November and in the Central Part - from September to December. The distribution of rainfall is given in figure 1c.

1.4 Time of wetness (TOW): High temperature and high humidity as well as great total of rainfall cause the long TOW all over country; it ranges in 4000 – 6000 h/year which is equivalent to 45 – 75 % of year-time. According to ISO 9223 standard [3] this means 45 – 75 % of year-time the air has RH > 80 % and T > 0 °C, in this duration atmospheric corrosion always occurs. It is well known that TOW increases with RH and T (when T > 0); however, it begins decrease when T > 10 – 11 °C because the evaporation of moisture from metal surface becomes faster [4]. Based on linear regression treatment of the data collected from more than 150 meteorological stations during period of 10 years, the relationship between TOW, T and RH was established with high correlation coefficient as follows:

$$TOW = -14.09T + 228.63RH - 13050 \qquad R^2 = 0.93.$$

Different from the temperate areas, in Vietnam TOW increases directly proportional to RH and inversely proportional to T. The map of TOW variation is shown in figure 1d.

1.5 Cl^- and SO_2 deposition rate: The air salinity (Cl^-) were determined at 13 test sites (Fig. 2) during one year using "wet candle" method according to ISO 9225 [5], at some sites the data were converted from the values obtained by "dry gauze" method using the formula

Cl^-_{wet} = $2Cl^-_{dry}$ [6]. The sulfur dioxide (SO_2) deposition rate was determined using alkalized paper shown in [5]. The results are given in Tab. 1

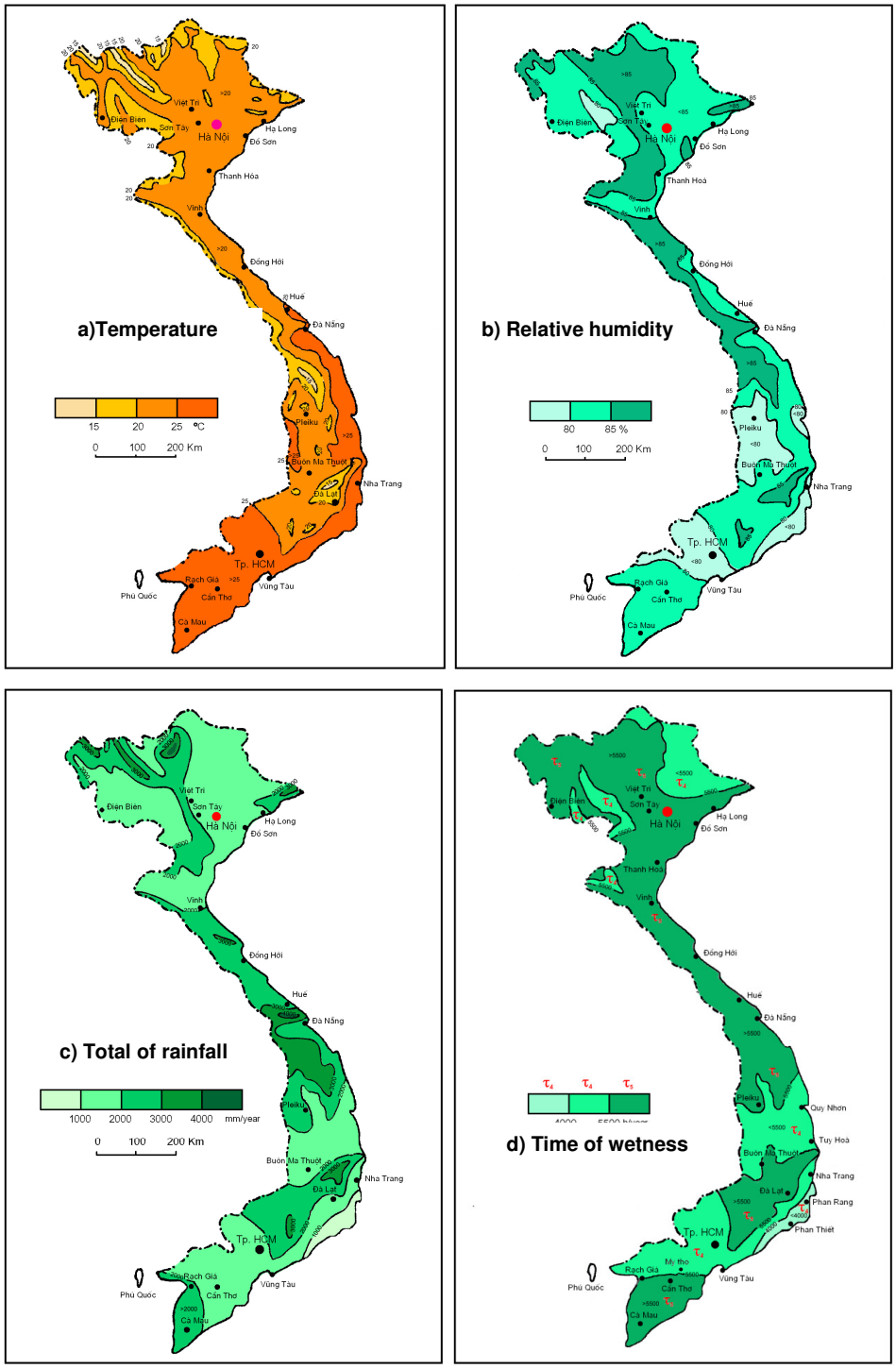

Figure 1. The maps of climate parameters.

Table 1. ISO 9223 corrosivity of atmosphere – Classification.

N°	Test sites	Cl^- mmd	ISO Categ	SO_2 mmd	ISO Categ	N°	Test sites	Cl^- mmd	ISO Categ	SO_2 mmd	ISO Categ
1	Dien Bien	1.16	S_0	No data	No data	**8**	Dong Hoi 1(*)	10.28	S_1	2.49	P_0
2	Viet Tri	1.88	S_0	6.67	P_0	**9**	Dong Hoi 2(*)	40.10	S_1		
3	Son Tay	1.50	S_0	7.92	P_0	**10**	Hue	1.33	S_0	0.98	P_0
4	Do Son	17.51	S_1	2.80	P_0	**11**	Da Nang	4.99	S_1	3.83	P_0
5	Hai Duong	6.89	S_1	6.01	P_0	**12**	Nha Trang	15.64	S_1	1.34	P_0
6	Ha Noi	2.24	S_0	7.95	P_0	**13**	Ho Chi Minh city	4.58	S_1	12.63	P_1
7	Thanh Hoa	3.48	S_1	3.90	P_0	**14**	Vung Tau	12.16	S_1	3.23	P_0

- Dong Hoi 1(*) is about 3km from the sea; Dong Hoi 2(*) is about 300 m from the seashore
- mmd = mg/m²day .

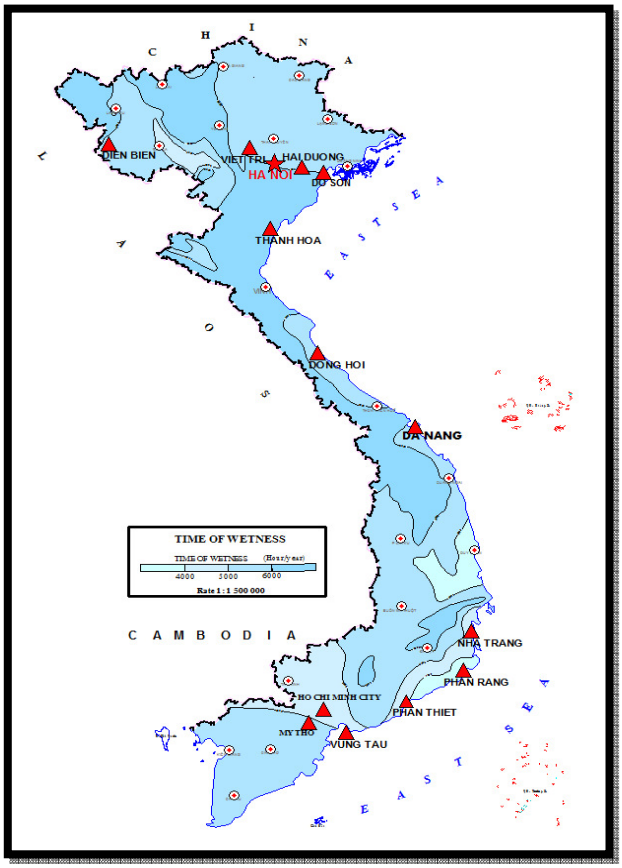

Figure 2. Location of the test sites.

Table 2. ISO Corrosivity of atmosphere based on Cl^- and SO_2 deposition rate [3].

Categ.	TOW, h/y	SO_2			Cl^-, mg/m^2.day	
		Categ.	µg/m^3	mg/m^2.d		
τ_1	<10	P_0	12	<10	S_0	<3
τ_2	10-250	P_1	12-40	10-35	S_1	3-60
τ_3	250-2500	P_2	40-90	35-80	S_2	60-300
τ_4	2500-5500	P_3	90-250	80-200	S_3	300-1000
τ_5	>5000					

1.6. ISO classification-Corrosivity of atmosphere: According to ISO 9223 [3] based on the values of TOW and Cl^-, SO_2 deposition rates as well as corrosion rate of one year-exposure, the atmosphere are classified into different levels that express the corrosivity of atmosphere (Tab. 2). It can be seen from Fig.1d and Tab. 2 that TOW of all regions in Vietnam is classified as highest categories - τ_4 &τ_5. The SO_2 deposition rate is insignificant with level P_0, except in Ha Noi and Ho Chi Minh City the SO_2 level is P_1 because all test site are located far from industrial zone. The Cl^- deposition rates are S_1 levels at the coastal sites and S_0 levels at the sites in land (Tab. 1).

3. COROSION OF CARBON STEEL

3.1. Long term exposure

Samples of carbon steel were exposed at 6 sites (see Fig. 2) that distribute in the North, the Middle and the South of country. The exposure periods are 1,2,3,4 and 5 years and the environmental parameters were collected during the time of exposure (Tab. 3). In general, the corrosion rates (CR) of carbon steel decrease with exposure time (Fig. 3a), perhaps due to the formation of corrosion products (CP) on the surface with more or less protectiveness. The corrosion rate decreases in the order: Do Son > Nha Trang > Da Nang > Ha Noi > Ho Chi Minh City > Vung Tau (Fig. 3a), thus it is clear that the CR of carbon steel strongly depends on TOW and Cl^- deposition rate (Tab. 3 and Fig. 3a).

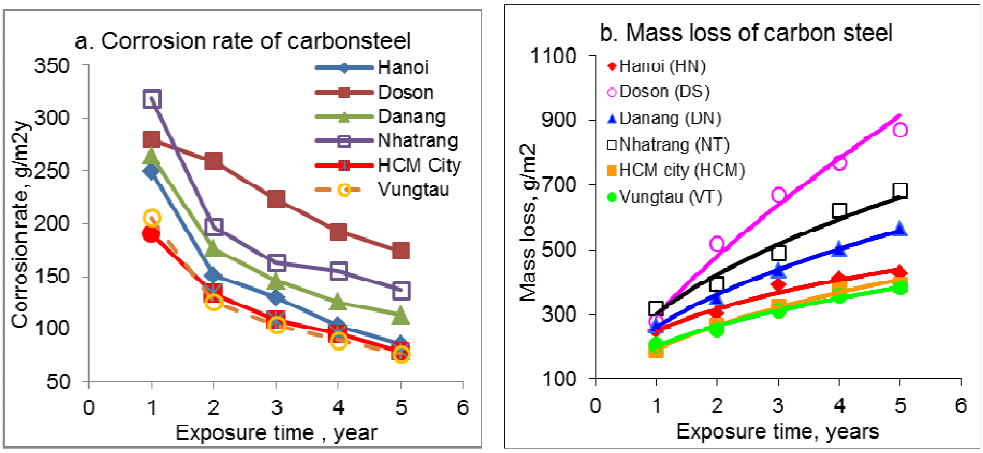

Figure 3. Corrosion rate (a) and corrosion loss (b) of carbon steel.

Table 3. Environmental parameters during the exposure time and A, n values of model $M = At^n$ for carbon steel.

Test sites	T°C	RH, %	TOW Giờ/y	Cl^- mg/m^2.d	SO_2 mg/m^2.d	A	n	R^2
Ha Noi	24.1	79.0	4726	0.48	8.44	247.88	0.36	0.96
Do Son	24.0	85.5	6406	11.72	2.62	295.65	0.70	0.98
Da Nang	25.8	83.5	5750	2.01	2.56	260.52	0.47	0.99
Nha Trang	26.7	80.6	4882	7.82	2.51	302.25	0.48	0.96
Ho Chi Minh City	25.8	79.3	4709	1.32	15.73	192.62	0.47	0.99
Vung Tau	27.4	77.7	4414	6.08	3.81	200.45	0.40	0.98

The data of corrosion mass loss depending on the exposure time were fitted the functions such as power, linear and logarithm, the results showed that the corrosion process of carbon steel mostly obeys the law of power model $M = At^n$ (Fig. 3b) with the values of A, t and n given in Tab. 3. The values $n < 0.5$ at almost test sites indicate that the diffusion process of the aggressive agents from environment decreases with time because the CP has more or less protective ability. However, different from the others, at Do Son site, the value $n > 0.5$ indicates the porous CP layer without protectiveness; consequently the environmental argents are easy to penetrate to the substrate. This law was used to express the atmospheric corrosion by the authors [7 - 9].

3.2. One-year exposure and corrosion mapping of carbon steel in non-coastal areas

In order to classify the corrosivity of atmosphere for carbon steel, an exposure program was carried out at 13 test sites and CR after the first year exposure were determined. Beside those data, the data collected from RAPIDC Program[(1)] were used to established the relationship between CR of carbon steel and environmental parameters. The data are expressed in Tab.5.

It is well known that the atmospheric corrosion is affected by the complex of environmental factors, and the atmospheric corrosion rate of carbon steel can be simulated by a multi-linear equation as follows:

$$K = a_1T + a_2RH + a_3TOW + a_4Rf + a_5Cl + a_6SO_2 + a_7 \quad (1)$$

here: K: corrosion rate, g/m^{2}y; T, °C; RH, %; TOW, h/y; Rf, mm/y; Cl & SO_2, mg/m^2.day; $a_1 \ldots a_7$: constants.

Because the SO_2 concentrations obtained at all test sites are insignificant, they perhaps do not dominate the corrosion of carbon steel, therefore they can be skipped, and thus CR is estimated by the following equation:

$$K = a_1T + a_2RH + a_3TOW + a_4Rf + a_5Cl + a_6 \quad (2)$$

The data in Tab.5 were used for regression analysis according to equation (2) and the following relationship was found out:

$$K = -13.874*T + 0.019*TOW + 0.672*Cl + 0.010*Rf + 455.896 \qquad R^2 = 74.3\ \% \quad (3)$$

$$\text{or } K = -14.123*T + 4.785*RH + 0.351*Cl + 193.726 \qquad R^2 = 71.5\ \% \quad (4)$$

The equation (3) is more correct, however it can be used when the data of TOW, Rf are available. The equation (4) is used more easily because the data of T and RH are always

available at the meteorological stations.

From equations (3 and 4) it is clear that in the macro-climate regions (except the micro-climate regions as heavy industrial areas) the CR of carbon steel is dominated by TOW, Cl^- deposition rate and total of rainfall. Especially, air temperature has an action of reducing corrosion of carbon steel due to decrease of TOW on steel surface; this is the typical characteristic of tropical climate which is quite different from moderate or cold areas where the CR of metals always increases with air temperature.

Table 5. Corrosion rate of carbon steel after one-year exposure and environmental parameters at test sites.

N°	Test sites	Test period	K, $g/m^2.y$	T, °C	RH, %	TOW, h/y	Cl^{**}, mmd	Rf, h/y
1.	Do Son	1995-1996	290.70	23.6	86.1	6359	30.5	1934
2.	Do Son	2003-2004	279.74	23.3	86.1	6081	17.51	1617
3.	Hai Duong	2003-2004	287.52	23.5	85.9	6226	6.89	1425
4.	Ha Noi	1995-1996	240.36	24.1	81.3	4697	0.64	1760
5.	Ha Noi	2003-2004	249.71	24.1	79.8	4917	2.24	1585
6.	Ha Noi	2002-2003*	181.85	24.7	79.0	4661	1.8	1556
7.	Ha Noi	2005-2006*	226.75	24.5	78.0	4435	1.76	1471
8.	Thanh Hoa	2003-2004	242.95	23.9	84.7	6158	3.48	1636
9.	Dong Hoi	2002-2003	255.76	24.8	82.6	5604	10.28	2153
10.	Hue	2003-2004	247.67	24.6	85.81	6001	1.33	3007
11.	Da Nang	1995-1996	274.02	25.9	83.1	5672	3.08	2015
12.	Da Nang	2003-2004	264.65	25.8	83.3	5701	4.99	2442
13.	Nha Trang	1995-1996	200.49	26.7	80.8	4651	19.3	1311
14.	Ho Chi Minh city	1995-1996	200.00	27.7	75.6	4205	1.22	1991
15.	Ho Chi Minh city	2003-2004	190.53	25.8	79.3	4612	4.58	2850
16.	Ho Chi Minh city	2002-2003*	163.65	28.3	74.0	3467	3.06	1441
17.	Ho Chi Minh city	2005-2006*	138.75	28	77.0	4157	2.66	1607
18.	Vung Tau	1995-1996	190.13	27.5	79.3	4495	13.58	1404
19.	Vung Tau	2003-2004	205.77	27.4	79.4	4400	16.5	1546
20.	My Tho (Tien Giang)	2002-2003*	166.05	27.0	81.0	5086	8.9	1222
21.	My Tho (Tien Giang)	2005-2006*	186.35	27.0	83.0	5543	8.9	1659
(*): Data obtained from RAPIDC Program								

The equations (3 and 4) were used to calculate CR of carbon steel at the areas without testing, and then the mapping corrosion was done preliminary.

It is recognized that at the test sites far from the sea (with chloride deposition rate < 3 mg/m^2.day), the chloride content contributes approximate 10 % to CR values calculated by equations (3&4), therefore this portion can be skipped when estimating the CR in the areas un-affected by Cl^-. Based on equations (3 and 4) the CR of carbon steel in non-coastal areas were estimated for more than 150 sites based on ten-year-average annual values of T, RH, TOW and Rf, from those data the corrosion map of carbon steel was built (Fig. 4).

On the map, corrosion rates were divided into five levels of range 150 – 400 g/m^2.y with 50 g/m^2.y difference. In general, the CR of carbon steel decreases from the North to the South and increases with elevation of topography. However, at the end of Vietnam (Ca Mau peninsular), the CR is higher in comparison with the nearby areas. In the driest regions such as Phan Rang, Phan Thiet and around Ho Chi Minh city (CR is less than 200 g/m^2.y). The CR is highest on the mountain areas due to high RH and long TOW; it reaches to 300 - 350 mg/m^2.y at the height of 700 – 1000 m.

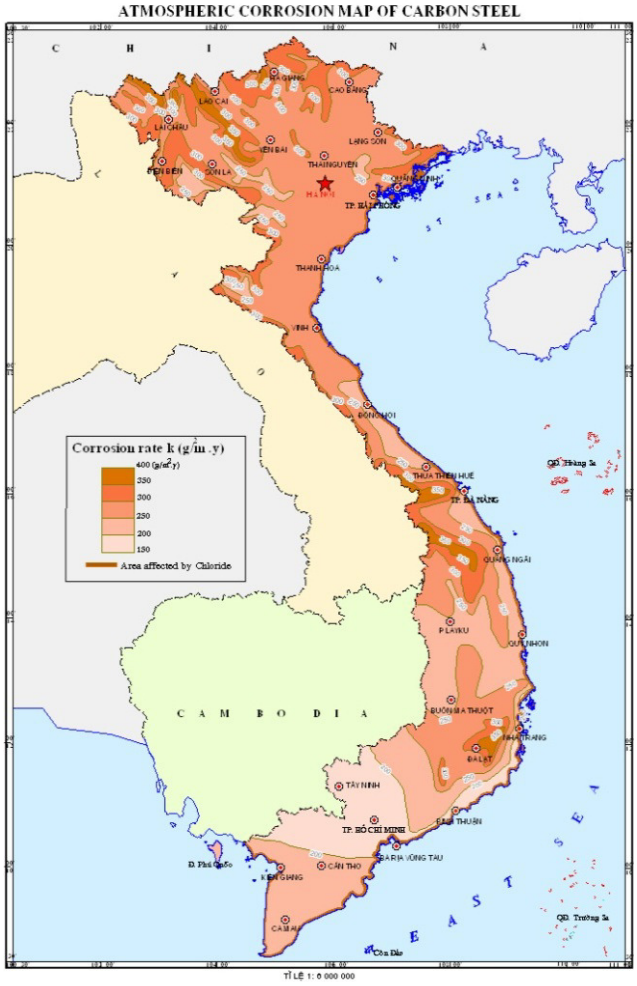

Figure 4. Corrosion map (one year corrosion rate) of carbon steel in non-coastal areas.

4. CORROSION OF ZINC COATINGS

The samples of zinc galvanized steel (ZG) and zinc sprayed coating (ZS) were also exposed at the same sites with carbon steel. The corrosion rates were determined after 6, 9 months, and 1, 2, 3, 4, 5 years of exposure by using weight loss method.

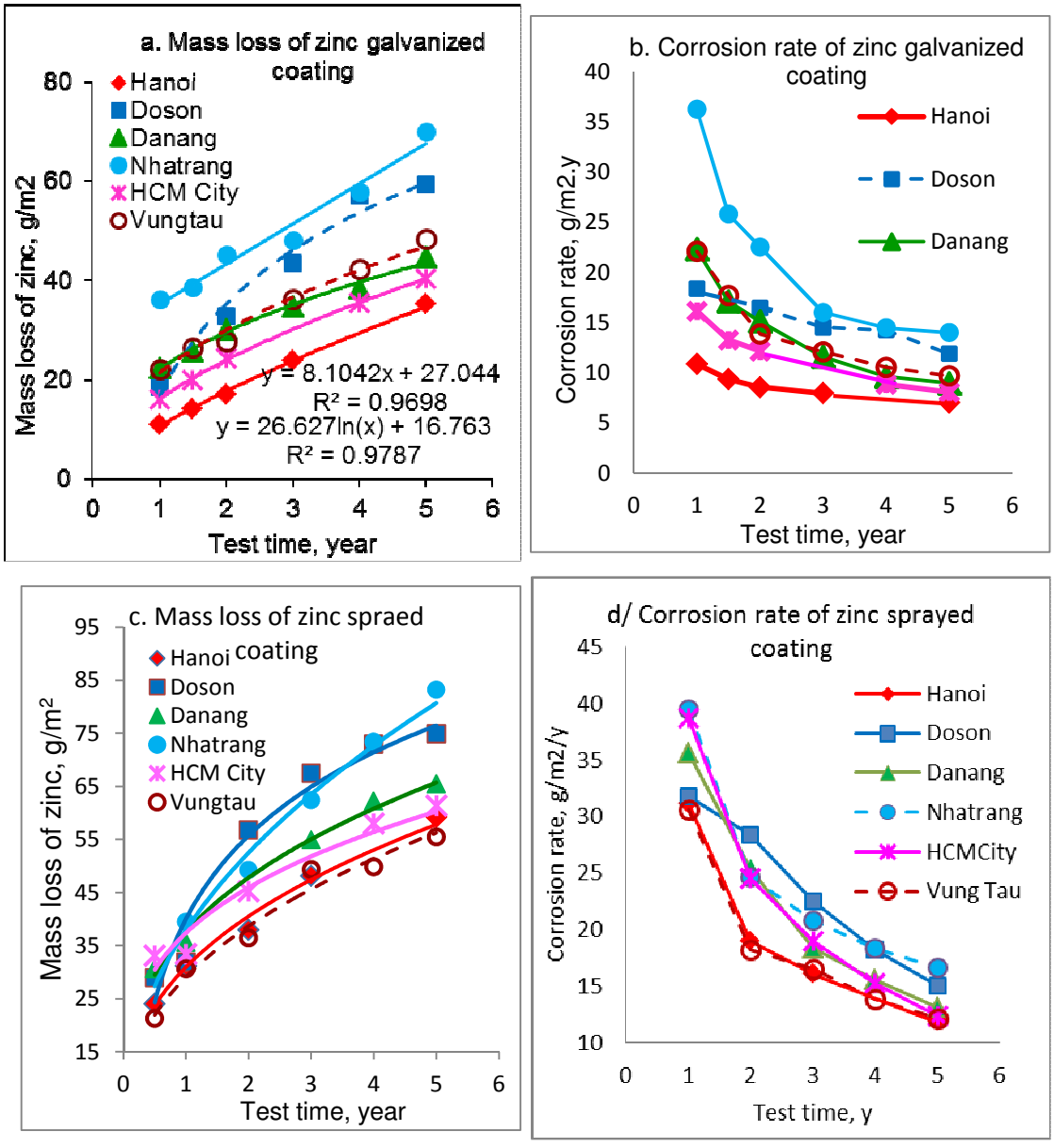

Figure 5. Time variation of corrosion of zinc galvanized coating (a, b) and zinc sprayed coating (c, d).

It can be seen on Fig. 5a and 5b that the corrosion rates of both ZG and ZS coatings gradually reduce at all sites due to more or less protective effect of CP on the surface. It seems that the corrosion of zinc coatings is accelerated by Cl^- deposition rate but not by TOW. The biggest corrosion of ZG coating is observed at coastal sites such as Nha Trang and Do Son that

have the highest Cl^- concentration, then CR is lower at Da Nang and Vung Tau that are far from the sea-shore. In Hanoi and Ho Chi Minh City corrosion are lowest.

In the case of ZS coating the corrosion rates are higher at the early stage, then decrease faster with time. The trend of corrosion is similar to ZG steel, however, in Ho Chi Minh City ZS coating was corroded stronger than that in Vung Tau. This might be explained by the heavy rain in Ho Chi Minh City which removes the CP layer on the surface as well as in the pores of ZS coating, consequently the corrosion increases. Similar to CS, the atmospheric corrosion of zinc coatings almost develops according to power law of type $M = At^n$ at almost test sites. Nevertheless at some severe sites such as Do Son and Nha Trang the corrosion process obeys on logarithm and linear law, respectively. This shows more or less protective ability of CP formed at Do Son; and on the contrary, non-protectiveness of CP on ZG coating exposed at Nha Trang (Tab.6).

Table 6. The values A and n of power laws of zinc coating.

Test sites	*Galvanized steel*			*Zinc sprayed coating*		
	A	n	R^2	A	N	R^2
Ha Noi	11.396	0.66	0.99	31.020	0.38	0.99
Do Son	$M = 26.63 \ln(t) + 16.76$		0.99	$M = 22.65 \ln(t) + 40$		0.95
Da Nang	22.502	0.40	0.99	38.343	0.35	0.97
Nha Trang	$M = 8.10t + 27.044$		0.97	38.984	0.45	0.98
Ho Chi Minh City	16.432	0.55	0.99	39.700	0.30	0.99
Vung Tau	21.153	0.50	0.98	28.337	0.47	0.98

The composition of CP formed on the zinc coatings were determined by X-diffraction technique. The main compounds are zincite - ZnO, zinc hydroxide-$Zn(OH)_2$, zinc hydroxycarbonate-$Zn_4CO_3(OH)_6.H_2O$, hydrozincite-$Zn_5(CO_3)_2(OH)_6.H_2O$, zinc hydroxychloride-$Zn_5(OH)_8Cl_2.H_2O$, zinc sulfate-$ZnSO_4$, zinc hydroxysulfate - $Zn_4SO_4(OH)_6.0.5H_2O$, zinc oxide sulfite- $ZnO.2ZnSO_3.3H_2O$. Among them the stable phase such as zinc hydroxychloride- $Zn_5(OH)_8Cl_2.H_2O$ was identified early on specimens exposed in coastal areas, perhaps the high air humidity favoured the formation of this phase that contributes to protectiveness of CP on zinc coatings. The protective ability of CP were investigated using EIS technique by the author [10].

5. CORROSION OF COPPER

Samples of technial copper were exposed at 7 test sites (Ha Noi, Do Son, Da Nang, Ho Chi Minh City, Vung Tau and Tien Giang). The results (Fig. 6a) show the highest corrosion at the coastal sites (Do Son, Da Nang and Vung Tau), then it decreases very fast due to the formation of copper oxides and stable compound in CP. At Ha Noi and Ho Chi Minh City, the CRs of copper are lower, however they decrease slowly, accordingly after four years they are not so different from site to site. The above mentioned results are also expressed by the relationship of corrosion with exposure time in Fig. 6b – the corrosion of copper follows power or logarithm law at Do Son, Da Nang,Vung Tau, Tien Giang and follows linear law at Ha Noi and Ho Chi Minh City. The X-ray diffraction analysis detected the composition of CP formed on copper surface to be cuprite-Cu_2O, brochantite- $Cu_4SO_4(OH)_6$. Atacamite-$Cu_2Cl(OH)_3$ appeared as the

main compound in the CP formed at Do Son. Besides, some other compounds such as eriochalcite-$CuCl_2.2H_2O$, ponsjakite- $Cu_4SO_4(OH)6.H_2O$ were found out as intermediate phases.

Cuprite is formed initially on copper surface exposed to atmosphere, brochantite characterizes the copper CP in urban/industrial areas, and atacamite is the main composition of CP on copper exposed in marine atmosphere [11, 12]. However, brochantite and atacamite early appeared at test sites of Vietnam, this may be promoted by high RH and long TOW.

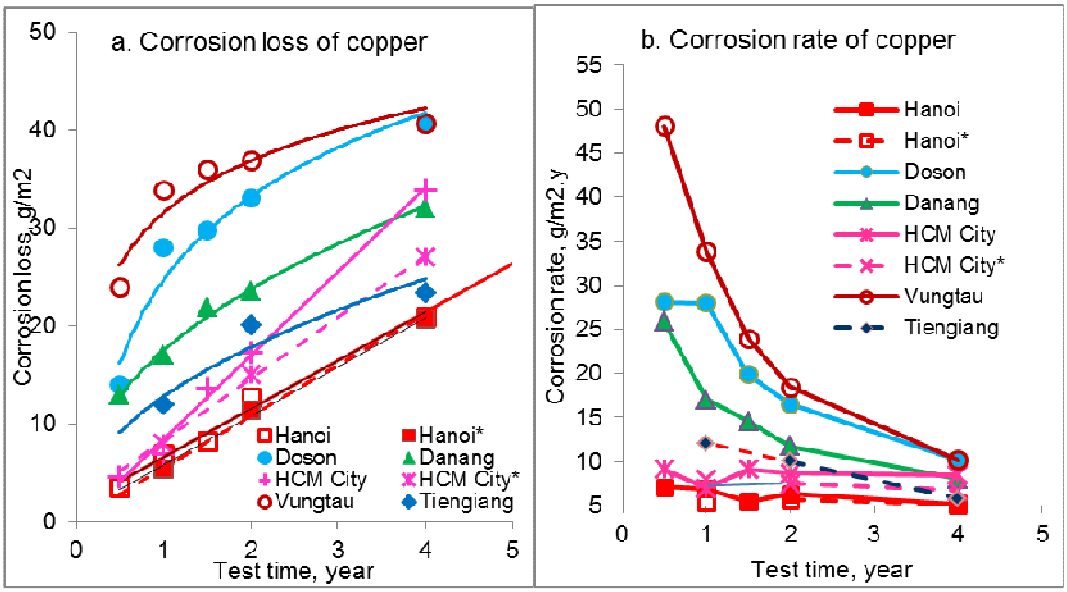

Figure 6. Time variation of copper corrosion with time.

6. CURRENT STUDY

Study on atmospheric corrosion has been continuing. The weathering steel has been tested at 4 sites (Ha Noi, Dong Hoi, Phan Rang and Ho Chi Minh City) for investigating the protective ability of CP layer in tropical climate of Vietnam. The preliminary results were presented at ICC18 Conference organized in Perth, Australia in Nov 2011 [13].

An E-Asian Project cooperated by Japan, Vietnam and Thailand has been implemented since 2013. This Project aims to build the corrosion maps of carbon steel, weathering steel, zinc galvanized steel and zinc-aluminium (55Al-Zn) for Asian areas. The results obtained from this project will contribute to adjusting the standards ISO on corrosion classification.

7. CONCLUSION REMARKS

Climate of Vietnam is characterized by high T& RH as well as very long time of wetness and great total of rainfall.

According to ISO classification, in Vietnam TOW categories are τ_4&τ_5 which increases the likelihood of corrosion occurring throughout the whole year.

Corrosion rate of carbon steel strongly depends on time of wetness, whereas the corrosions of zinc coatings and copper are predominantly dominated by chloride deposition rate.

The corrosion of carbon steel develops according to power law, but in the case of zinc coatings and copper the corrosion process follows not only power but also logarithm and linear.

The corrosion map for carbon steel was built for non-coastal areas that will be verified and extended by data obtained from the continued investigations in the near future.

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TÓM TẮT

TÓM TẮT CÁC KẾT QUẢ NGHIÊN CỨU ĂN MÒN TRONG MÔI TRƯỜNG KHÍ QUYỂN TẠI VIỆT NAM

Lê Thi Hồng Liên

Trung tâm Đánh giá hư hỏng vật liệu, Viện Khoa học vật liệu, Viện Hàn lâm KHCNVN, 18 Hoàng Quốc Việt, Cầu Giấy, Hà Nội

Email: *honglien@ims.vast.ac.vn*

Bài báo giới thiệu tóm tắt một số kết quả nghiên cứu ăn mòn kim loại trong điều kiện khí quyển Việt Nam từ năm 1995 đến nay, bao gồm ăn mòn thép các bon, các lớp phủ kẽm và đồng kim loại. Các đặc điểm khí hậu và tốc độ sa lắng của ion clorua và khí SO_2 được xác định trong cùng thời kỳ thử nghiệm. Các kết quả cho thấy tốc độ ăn mòn thép các bon được gia tốc chủ yếu bởi thời gian lưu ẩm bề mặt, tốc độ ăn mòn giảm khi nhiệt độ tăng, trong khi đó, ăn mòn các lớp phủ kẽm và đồng kim loại thì dường như không bị khống chế bởi độ ẩm mà bởi hàm lượng muối trong khí quyển và các yếu tố khác như chế độ mưa, hàm lượng SO_2 khí quyển… Trong các vùng khí quyển ven biển, hàm lượng ion Cl^- đóng vai trò gia tốc ăn mòn đối với tất cả các kim loại đã thử nghiệm. Các số liệu thử nghiệm dài hạn chỉ ra rằng quá trình ăn mòn các kim loại thử nghiệm phát triển chủ yếu theo quy luật hàm mũ, tuy nhiên, trong một số trường hợp quá trình ăn mòn lại tuân theo quy luật đường thẳng hoặc quy luật logarit tùy thuộc vào lớp sản phẩm ăn mòn tạo thành trên bề mặt kim loại. Mức độ ăn mòn của các vùng khí hậu Việt Nam được phân loại theo tiêu chuẩn ISO 9223 dựa trên các số liệu thời gian lưu ẩm bề mặt, hàm lượng SO_2 và Cl^- trong khí quyển. Bản đồ ăn mòn thép các bon bước đầu được xây dựng cho các vùng khí hậu xa biển. Các hoạt động nghiên cứu hiện tại và trong thời gian sắp tới cũng được đề cập đến trong bài báo.

Từ khóa: ăn mòn trong điều kiện khí quyển, thời gian lưu ẩm, mức độ ăn mòn, bản đồ ăn mòn.