Corrosion of Different Types of Steel in Atmospheric and Tidal Marine Environment of Thailand

Prasong Permsuwan[1], Pakawat Sancharoen[2], Somnuk Tangtermsirikul[3], Paiboon Sreearunothai[4], and Ekkarut Viyanit[5]

[1] Graduate student, School of Civil Engineering and Technology, Sirindhorn International Institute of Technology, Thammasat University, Thailand

[2] Researcher, Construction and Maintenance Technology Research Center, Sirindhorn International Institute of Technology, Thammasat University, Thailand

[3] Professor, School of Civil Engineering and Technology, Sirindhorn International Institute of Technology, Thammasat University, Thailand

[4] Lecturer, School of Bio-Chemical Engineering and Technology (BCET), Sirindhorn International Institute of Technology, Thammasat University, Thailand

[5] Researcher, National Metal and Materials Technology Center (MTEC), 114 Thailand Science Park, Thailand

Tel. 02-986-9009 ext 3002, Fax 02-986-9009 ext 3001, E-mail: prasong_civilnu@hotmail.com

Abstract

Structural steels which are hot-rolled steel grade SS400 according to JIS G3101, hot-rolled steel grade SM490YA according to JIS G3106 and hot-rolled atmospheric corrosion resisting steel grade SMA490A according to JIS G3114 were exposed from January 2010 until January 2011 to marine and industrial environment at Maptapud industrial estate, Rayong, Thailand. Specimens were exposed in two environmental conditions which were atmospheric zone and tidal zone. The corrosion rate of specimens was investigated by weight loss measurement. Also, environmental conditions such as temperature, relative humidity, and chloride deposition were monitored monthly. Finally, the results showed that corrosion rate at 12 months of carbon steel was higher than that of corrosion resisting steel (SS400 > SM490YA > SMA490A). Furthermore, the specimens in tidal zone showed higher corrosion rate than those in atmospheric zone obviously due to effects of biofouling and wet-dry condition. Also, life cycle cost of a structure constructed by SS400, SM490YA and SMA490A steels exposed to atmospheric and tidal zones was compared. The results can be used for material selection and service life design of steel structures in Thailand.

1. Introduction

Structural design of both reinforced concrete and steel structures consider mainly the strength of members. But durability design or service life design, which also affects the safety of structure, is rarely concerned. Particularly, the steel can be deteriorated rapidly when it is subjected to corrosive environmental condition. Corrosion is a major problem affecting safety and serviceability of steel structures because it can cause reduction of cross sectional area of the structural members. Consequently, consideration of corrosion resistance of materials is important for designing service life of steel structures.

Atmospheric corrosion is an electrochemical reaction occurring on metal surface in a presence of thin film electrolyte [3]. In case of atmospheric corrosion, structural steel in marine environment deteriorates primarily by climatic factors such as temperature, relative humidity, and the presence of chloride and SO_2. Normally, rust formed on

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surface of carbon steel is porous with poor adherent, and cracked at the outer part [4]. This phenomena causes oxygen, water, Cl^- and SO_2 from outside to penetrate to the steel substrate easily [4,5]. For corrosion resisting steel, at the early stage, the rust is formed similarly to the carbon steel. But as the exposure time increased, the rust layer becomes more compact, denser, and tighter [6-7]. For this reason, the rust layer acts as the barrier to inhibit corrosive species and then the rate of corrosion is decreased.

In Thailand, environmental conditions are different from other countries. There is no sufficient data of atmospheric corrosion to model or predict steel corrosion in order to design service life of steel structures in Thailand. Also, there is limited information on atmospheric and tidal corrosion. In addition, the standard currently used to design steel structures in Thailand was adopted from other countries. It is essential to study the corrosion behavior of structural steel in Thailand. The aim of this paper was to investigate the corrosion behavior of SS400, SM490YA and SMA490A steels.

2. Experimental Program

2.1 Specimen preparation

The materials tested in this study are three kinds of structural steel; 1) hot-rolled steels for general structure grade SS400 according to JIS G3101, 2) hot-rolled steels for welded structure grade SM490YA according to JIS G3106, and 3) hot-rolled atmospheric corrosion resisting steels for welded structure grade SMA490A according to JIS G3114. Their chemical compositions determined by spark emission spectrometer are shown in Table 1 together with the specified values in the standard. ISO 8565 standard specification suggests the following procedures for specimen preparation before exposure test. Specimens were cut from the steel plate to the size of 150×70×3 mm for SS400 and SM490YA steels, and 150×70×5 mm for SMA490A steel. The mill scale on the surface of the specimens was mechanically removed by sand blasting and then wet-polished by 600 grade sand paper on all surfaces. Finally, the specimens were rinsed with distilled water and ethyl alcohol, dried by blower, weighted and immediately placed in desiccators.

2.2 Exposure test

Exposure site is located at Maptapud industrial estate, Rayong, Thailand as shown in Fig. 1. The ground position coordinates of this location is 12° 39’ northern latitude and 101° 10’ eastern longitudes. Even though,

Table 1 Chemical compositions of different types of steel

Steel types	Chemical composition (% by wt)									
	C	Si	Mn	P	S	Cr	Ni	Cu	Al	Mo
Standard JIS G3106	≤ 0.20	≤ 0.55	≤ 1.65	≤ 0.035	≤ 0.035	-	-	-	-	-
SM490YA	0.070	0.218	0.352	0.009	0.016	0.031	0.073	0.154	0.013	0.015
Standard JIS G3101	-	-	-	≤ 0.05	≤ 0.05	-	-	-	-	-
SS400	0.047	0.174	1.039	0.010	0.006	0.026	-	-	-	-
Standard JIS G3114	≤ 0.18	0.15-0.65	≤ 1.4	≤ 0.035	≤ 0.035	0.45-0.75	0.05-0.30	0.30-0.50	-	-
SMA490A	0.115	0.396	0.368	0.076	0.005	0.681	0.16	0.368	0.021	0.003

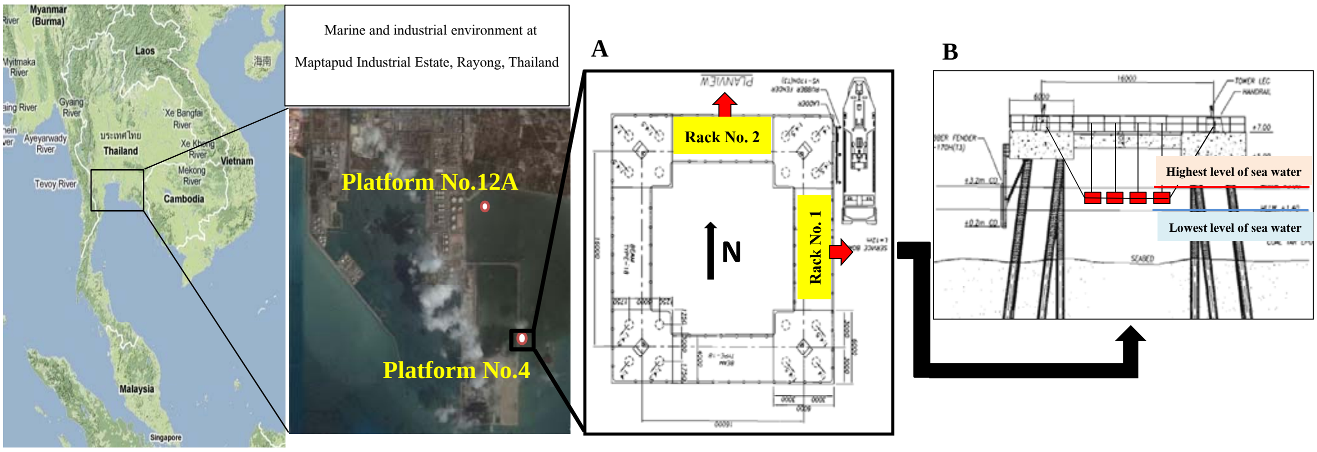

Fig. 1 Photograph and detail and drawing of the exposure site: (A) atmospheric exposure (B) tidal exposure

environment of exposure site is marine environment but this area is also an industrial area with power plant, oil refinery, chemical industry, etc. The experiment was conducted from January 2010 to January 2011. The exposure test was conducted in two conditions which were atmospheric and tidal zone exposure.

For atmospheric exposure, two exposure racks that were carried out according to ISO 8565 were set on the transmission tower platform No. 4 only. Rack No.1 faced to the East and rack No.2 faced to the North directions with the rack plane angle of 45° to horizontal as shown in Figs.1 and 2. For tidal exposure, sample storing cell made of plastic box were installed under the transmission tower platform number 4 and 12A of which water quality are different. The position of the boxes was set in the middle between the highest and the lowest sea water level in order to simulate wet-dry condition as shown in Figs.1 and 2. Environmental conditions such as temperature and relative humidity were monitored monthly by sensors connected to a data logger near the rack No.1. The results are shown in Table 2.

Fig.2 The exposure rack of atmospheric zone (left) and tidal zone (right)

Chloride deposition rate was measured monthly by using the wet candle method according to ISO 9225, and surface of wet candle exposed to atmosphere is 100 cm^2 as shown in Fig. 3. Also, the wet plate modified from standard wet candle method was installed in 4 directions in order to measure effect of wind directions on chloride deposition rate as shown in Fig. 3. The results are shown in Table 2.

Fig.3 The wet candle installed on the rack No.2 (left) and the wet plate installed at the leg of transmission tower (right)

Table 2 Atmospheric conditions and sea water properties

Atmospheric conditions			Sea water properties			
Monthly average temperature (°C)	Monthly average relative humidity (%)	Monthly average Cl^- deposition (mg/(m^2.day))	Chloride (ppm)		Sulfate (ppm)	
			Tower4	Tower12A	Tower4	Tower12A
30.6	61.3	22.5	19586	18821	3147	3041

The sea water properties, mainly chloride and sulfate concentration, were measured by Ion-chromatography. The results are shown in Table 2.

After 1, 3, 6 and 12 months, exposed specimens and monitored data were collected for analysis. Corrosion products were removed chemically by HCl acid etching according to ISO 8407. After corrosion products had been removed completely, the specimens were rinsed with ethanol, dried with blower and weighted to measure weight loss.

3. Results and Discussion

3.1 Environmental characteristics at exposure site

The environmental characteristics measured at the exposure sites are shown in Table 2. According to ISO 9223, environmental conditions are classified in term of chloride deposition rate (class S) and sulfur dioxide deposition rate (class P). Also, Time of wetness (TOW) (class τ), the period of time when relative humidity is greater than 80% and temperature is greater than 0°C, is also used for the classification. Environmental condition of exposure site is classified as S_1 because chloride deposition rate is 22.47 mg/m^2.day which is between 3-60 mg/m^2.day. Environmental condition is classified as class τ_3 because TOW is 9.1% which is between $3 < \tau \leq 30$ %. Also, the corrosive categories of the exposure site can be classified as C2 (low) to C4 (high) class by S_1 and τ_3 depending on classification of sulfur dioxide. The result of the wet plate shows that chloride deposition of rack No. 2 facing north is higher than rack No. 1 facing east because of the wind direction.

3.2 Thickness loss

Fig. 4 shows examples of the surface appearance of SS400 steel after 12 months exposure at atmospheric and tidal zone. In atmospheric zone, dark-brown rust product uniformly covered the entire surface while uneven surface was observed in specimens exposed to tidal zone and were covered with tightly attaching biofouling. Other types of steel showed similar appearance after 12 months exposure.

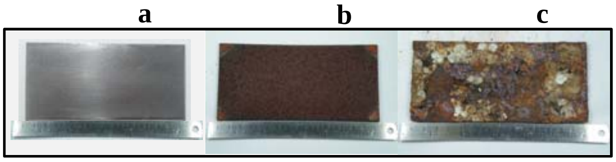

Fig.4. Appearance of SS400 steel: (a) before exposure, (b) after 12 months of exposure in atmospheric condition and (c) after 12 months of exposure in tidal condition

Generally, the corrosion rate of steel exposed to real environment was often calculated in term of thickness loss. The equation used to calculate thickness loss is shown in Eq.1

$$C = \frac{w}{\rho A} \times 10^4 \qquad (1)$$

where C is the thickness loss (µm), w is the weight loss (g) of specimen after being exposed, ρ is the density of the steel (7.86 g/cm^3) and A is the exposed area of the specimen (both sides) (cm^2). Figs. 5 and 6 show thickness loss of SS400, SM490YA and SMA490A steels exposed to atmospheric zone for 12 months on rack No.1 and rack No.2, respectively. In both exposure racks, the thickness loss of SS400, SM490YA and SMA490A steels continuously increased from the beginning to 12 months but the rate of corrosion decreased. Especially, corrosion rate of SMA490A steel obviously decreased at the long term because rust layer becomes more compact and denser.

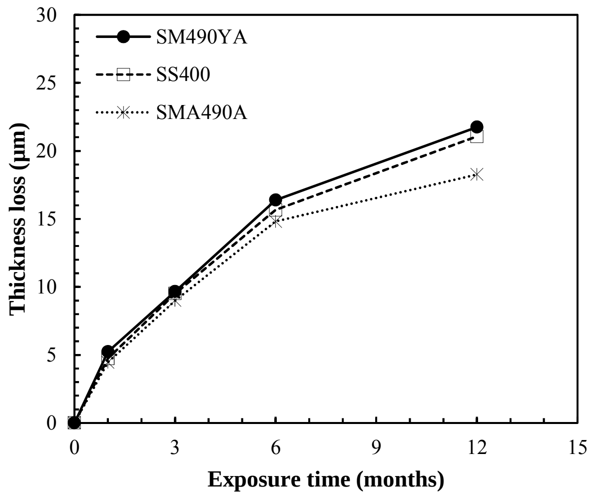

Fig.5 Thickness loss of specimens versus exposure time of rack No.1 at atmospheric zone

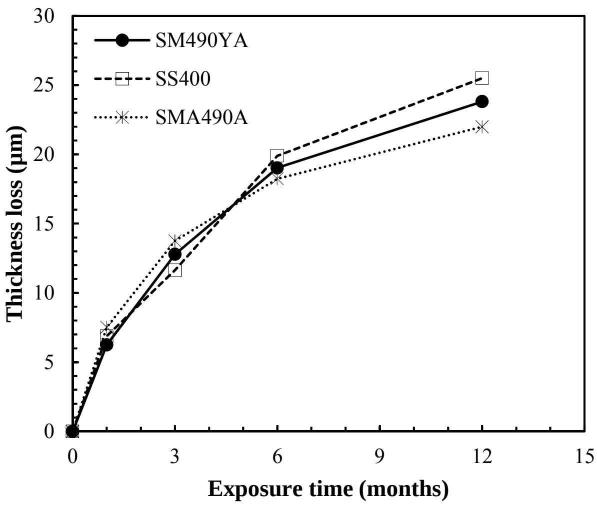

Fig.6 Thickness loss of specimens versus exposure time of rack No.2 at atmospheric zone

The thickness loss of SS400, SM490YA and SMA490A steels exposed to tidal zone after 12 months under platform No.4 and 12A are shown in Figs. 7 and 8. In tidal zone, the thickness loss of specimens is very high (greater than 200 μm) after 12 months of exposure. In both platforms, thickness loss of SMA490A is the lowest because of its alloying composition. Particularly, rate of corrosion of specimens under platform No.4 shows almost constant increasing without effect of protective rust layer. As the results, the thickness loss of specimens under platform No.4 is significantly higher than those under platform No.12A. This is because a better water quality such as higher O_2 content which causes fast growing of biofouling as well as accelerates steel corrosion directly was observed under platform No.4.

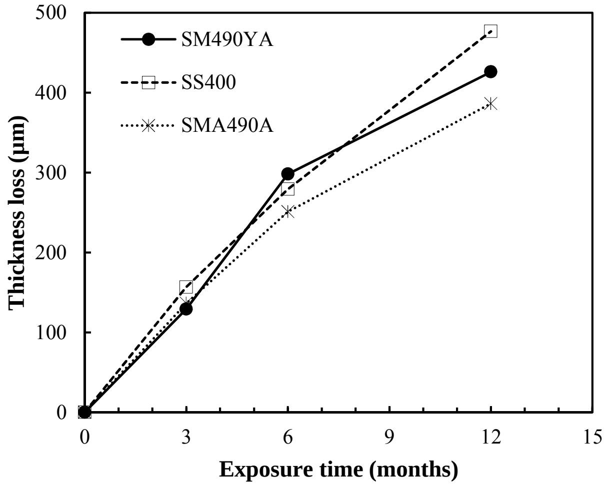

Fig.7 Thickness loss of specimens versus exposure time under platform No.4 at tidal zone

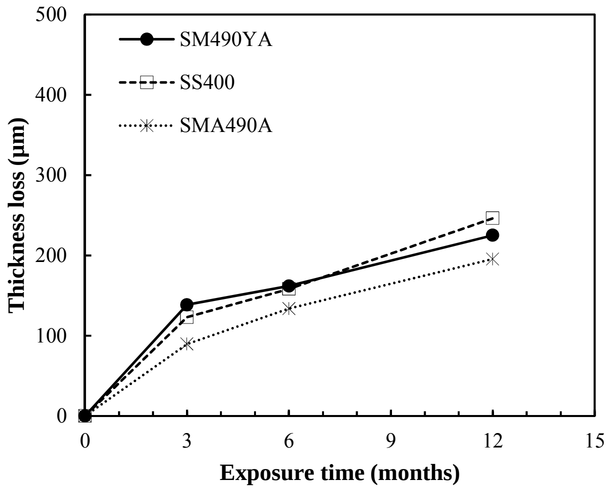

Fig.8 Thickness loss of specimens versus exposure time under platform No.12A at tidal zone

3.3 Corrosion rate

The prediction of corrosion rate of steel exposed to atmospheric condition was proposed by several researchers [4, 5, 6] as a bi-logarithmic equation as shown in Eq.2. This equation usually fits well with corrosion behavior over time.

$$C = At^{B} \tag{2}$$

where C is the thickness loss (μm), t is the exposure time (month), and A, B are constants. The constants A and B can be determined by plot in log-log coordinate between steel thickness loss and exposure time. The regression analysis was conducted in log-log coordinate to determine values of constants A and B value.

For corrosion rate prediction equation, several researchers [4, 7] considered the B value as the growth law of corrosion product: parabolic or linear. If the B value is in the range of 0.5 to 1, the corrosion products do not significantly protect the steel surface from corrosion and is called a linear growth. On the other hand, if the B value is lower than 0.5, it indicates a parabolic growth by formation of protective rust layers to reduce rate of corrosion in the long term.

The corrosion rates per year and the values of A, B constant in all exposure zones of SS400, SM490YA and SMA490A steels were calculated from the bilogarithimic equation and shown in Table 3.

For atmospheric zone, the corrosion rate of rolled steel (SS400 and SM490YA) is higher than corrosion resisting steel (SMA490A) in both racks because B value of SS400 and SM490YA are higher than 0.5 which indicate high rate of corrosion. The key factor causing the difference of corrosion rate is the chemical composition of the steel. The corrosion rate of SMA490A

Table 3 Corrosion rate and constant values of specimens

Steel type	Condition	Location	Corrosion rate (μm/year)	A	B
SM490YA	Atmospheric	Rack 1	22.68	5.25	0.59
		Rack 2	25.86	6.59	0.55
	Tidal	Under 4	461.42	54.45	0.86
		Under 12A	218.63	91.62	0.35
SS400	Atmospheric	Rack 1	22.21	4.83	0.61
		Rack 2	26.50	6.81	0.55
	Tidal	Under 4	480.29	65.46	0.80
		Under 12A	238.6	68.71	0.50
SMA490A	Atmospheric	Rack 1	19.93	4.63	0.59
		Rack 2	23.53	7.93	0.44
	Tidal	Under 4	398.53	61.66	0.75
		Under 12A	196.18	48.31	0.56

is the lowest because the corrosion resisting steel contains some alloy elements such as Cu, Cr, and Ni that improve the corrosion resistance as shown in Table 1. Q.C. Zhang et al [2, 7] has studied the distribution of alloying elements during formation of rust layers. They reported that the presence of Cu restrains the supply of oxygen, retards the anodic dissolution and reduces the electronic conductivity of rust layers. For this reason, the corrosion rate of SMA490A steel is reduced. The corrosion rate of rack No.2 is higher than that of rack No.1 for all types of steel because rack No.2 is affected by the wind direction making higher Cl^- deposition rate on the specimen surface from the results of wet-plate. This shows the importance of the effect of local environmental conditions on steel corrosion. From the result, the corrosive category of environment at exposure site can be defined as class C3 (medium) based on ISO 9223.

In case of tidal zone corrosion, the corrosion rate of tidal zone is significantly more aggressive than atmospheric zone. The corrosion rates of tidal zone and atmospheric zone show the difference of more than 10 times. The high Cl^- concentration and wetting in tidal zone accelerate corrosion process. Also, the effect of biofouling increased corrosion rate significantly. Biofouling is considered a major factor to control the corrosion behavior since the biofouling attached to the surface of steel tightly. Biofouling consumes oxygen, while supplies acid due to its excretion. As a result, steel subjects to extra corrosion due to acid [8]. In term of location, corrosion of specimens under platform No.4 is more severe than that of the specimens under platform No.12A because the differences in Cl^-, sulfate and oxygen concentration. Moreover, specimens under platform No.12A is located in calm sea water and low water quality that has low oxygen concentration causing slow activity and slow growing of biofouling [9].

The typical rates of corrosion for structural steel suggested by BS 6349-1 standard are shown in Table 4. BS 6349-1 standard recommends the corrosion rate for steel structure design in various exposure zones. The results of this study show that average corrosion rates in atmospheric zone are 25, 26 and 23 µm/year for SM490YA, SS400 and SMA490A, respectively. So the standard is acceptable to be used to design steel structures in atmospheric zone in Thailand. On the other hands, the results of average corrosion rates in tidal zone in this study are 461, 480, and 398 µm/year for SM490YA, SS400 and SMA490A, respectively. The standard recommends maximum limit of 100 µm/year. Therefore, the standard is not suitable for steel structure design in tidal zone in Thailand.

Table 4 Typical rates of corrosion for structural steels temperate climates (BS 6349-1)

Exposure zone	Corrosion rate µm/year		Results of the study µm/year		
	Mean	Upper limit*	SM490YA	SS400	SMA490A
Atmospheric zone	**40**	**100**	**25**	**26**	**23**
Splah zone	80	170	-	-	-
Tidal zone	**40**	**100**	**461**	**480**	**398**
Seawater immersion zone	40	130	-	-	-

**The upper limit is the 95% probability values*

3.4 Life cycle cost

Life cycle cost is the total cost of ownership of machinery, equipment and structure, including its cost of acquisition, operation, maintenance, and conversion [9]. In this paper, the SS400, SM490YA and SMA490A steels were analyzed when they are used to construct steel structure for service life of 50 years as shown in Table 5. This calculation only considered increasing thickness necessary to resist corrosion for 50 years according to Eq. 2 and Table 3. The unit cost was obtained from steel venders in Thailand in 2011. The results show that life cycle cost of SS400 steel for 50 years design is the lowest. Even though, the corrosion rate of SMA490A steel is the lowest but life cycle cost at 50 years is the highest. Because unit cost of SMA490A steel is very high. However, the increased dead load must be considered when they are applied to real construction.

Table 5 Life cycle cost of SM490YA, SS400 and SMA490A steels at 50 years of service life design

Steel Type	Unit cost (bath/kg)	Weight loss after 50 years (kg/m^2)		Cost (Unit cost x weight loss)			
		Atmosperic	Tidal	Atmosperic		Tidal	
				($bath/m^2$)	(Percent)	($bath/m^2$)	(Percent)
SS400	26	17.68	868.85	**460**	100	**22590**	100
SM490YA	35	17.45	1047.32	**611**	133	**36656**	162
SMA490A	85	10.25	590.56	**871**	189	**50197**	222

4. Conclusions

1. Corrosion resistance of SMA490A steel is the best in all conditions due to its chemical compositions, improving the characteristic of protective rust layers.
2. Corrosivity of sea water in tidal zone is significantly higher than atmospheric environment. This phenomenon is contributed by the effects of biofouling and high chloride concentration. Corroding mechanism of biofouling problem must be concerned in tidal zone corrosion and studied in the future.
3. Calculation of corrosion rate specified in the BS 6349-1 standard might not be suitable for structural steels exposed to Thailand environments especially for tidal zone corrosion.
4. In term of life cycle cost, SS400 steel is better than other steels for service life of 50 years design but the increased dead load must be considered.

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