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Application of High Performance Coatings for Service Life Extension of Steel Bridge Coatings

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In this study, performance tests, a field evaluation, and a life cycle cost (LCC) analysis for high performance coating systems were conducted to prepare a plan to reduce the cost of maintenance coating and contribute to the service life extension of steel bridges by applying high performance coatings to steel bridges that will be constructed in the future. From the deterioration models based on the field evaluation for chlorinated rubber and urethane topcoat systems, which have been applied often, the mean service lives were derived as 20.8 and 26.6 years, respectively. For the other coating systems that have not been applied in practice, the coordination factors were differentially applied with evaluation items. The most durable coating system was predicted to be thermal spray coating (TSC) primer/epoxy intermediate coat/fluoride resin topcoat, with a predicted value as long as 42.2 years. The LCC analysis indicates that partial application of high performance coating, such as TSC and fluoride resin, to specific parts vulnerable to corrosion and ultraviolet ray (UV) is more advantageous than the use of general coating systems.

Keywords: *High performance coating, Steel Bridge, Life cycle cost, Coating life prediction*

1. Introduction

In steel bridge coating, most working process of new coating for newly-established bridge is carried out in plant, whereas maintenance coating process is executed entirely in field. Such a difference generally lead to more coating defects and shortened service life of maintenance coating. Most of previous research projects on steel bridge coatings carried out by Korea Expressway Corporation Research Institute were focused on maintenance coating for that reason. However, in order to find fundamental solution for maintenance coating problem, service life extension of new coating and reduction of maintenance coating frequency are required. This study was carried out to prepare plans for reduction of maintenance coating cost and extension of coating life for steel bridge.

Thermal spray coatings (TSCs) are used extensively for the corrosion protection of steel and iron in a wide range of environments. The corrosion tests carried out by American Welding Society and the 34 and 44 year marine-atmosphere performance reports of the LaQue Center for Corrosion Technology confirm the effectiveness of flame sprayed aluminum and zinc coatings over long periods of time in a wide range of hostile environments [1-3].

U.S. Army Corps of Engineers (USACE) has experience with 85-15 zinc-aluminum alloy coating providing 10 years of service in very turbulent ice- and debris-laden water [4]. Table 1 shows typical service lives of paint coatings and predicted service life of TSCs for selected USACE applications.

2. Experimental and Field Evaluation Methods

Coating systems in which inorganic zinc (IOZ) and TSCs were used as primer were selected for performance tests as shown in Table 2. All the specimens were prepared as the same process with the coating method in field according to 'Standard Specification for Steel Structure Construction' [5].

For evaluation of weatherability, accelerated weather-o-tests (UV-condensation and xenon-arc type) and measurements of color difference, gloss retention, etc. were carried out. In the UV-condensation type accelerated test, specimens were alternatively exposed to UV using UVB-313 lamps in 60 ºC for 8 hours and moisture by

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Table 1. Predicted service life for selected thermal spray applications by USACE

Application	Paint System	Typical Service Life	TSC System (minimum/average TSC thickness)	Predicted TSC Life
Penstocks	Coal tar epoxy	20~30 years	360/400 μm 85/15 Zn/Al	30~40 years
Tainter gates	Vinyl zinc-rich	20~25 years	360/400 μm 85/15 Zn/Al	25~35 years
Tainter and roller gates (interior)	Vinyl	25~40 years	360/400 μm 85/15 Zn/Al	40~50 years
Tainter gates (very turbulent ice- and debris-laden water)	Vinyl zinc-rich	1~2 years	360/400 μm 85/15 Zn/Al	8~12 years
Roller gates	Vinyl zinc-rich	25~30 years	360/400 μm 85/15 Zn/Al	30~40 years
Service bridges	Alkyd/phenolic	10~15 years	250/300 μm 85/15 Zn/Al or Zn	50~60 years
Sector gates (seawater)	Epoxy zinc-rich/ coal tar epoxy	15~20 years	200~250 μm Al	20~40 years

Table 2. Coating systems used for tests

Specimen	Topcoat type	Coating layer				
		1	2	3	4	5
U1	Urethane	IOZ	Mist coat	High build epoxy	Urethane	Urethane
		75 μm	80 μm		30 μm	30 μm
U2		Zn-Al TSC	Mist coat	High build epoxy	Urethane	Urethane
		100 μm	100 μm		40 μm	40 μm
C1	Ceramic-urethane	IOZ	Mist coat	Ceramic type	Ceramic-urethane	Ceramic-urethane
		75 μm	75 μm		40 μm	35 μm
C2		Zn-Al TSC	Mist coat	Ceramic type	Ceramic-urethane	Ceramic-urethane
		100 μm	100 μm		40 μm	40 μm
S1	Siloxane	IOZ	Mist coat	High build epoxy	Siloxane	Siloxane
		75 μm	80 μm		30 μm	30 μm
S2		Zn-Al TSC	Mist coat	High build epoxy	Siloxane	Siloxane
		100 μm	80 μm		30 μm	30 μm
F1	Fluoride resin	IOZ	Mist coat	High build epoxy	Fluoride resin	Fluoride resin
		75 μm	100 μm		25 μm	25 μm
F2		Zn-Al TSC	Mist coat	High build epoxy	Fluoride resin	Fluoride resin
		100 μm	100 μm		25 μm	25 μm

condensation in 40 ºC for 4 hours, according to KS M 5982. In the xenon-arc type accelerated test, specimens were alternatively exposed to xenon light for 102 minutes and both of light and water for 18 minutes using Ci4000 manufactured by Atlas Ltd. according to ASTM G 155-1.

In order to establish deterioration model of steel bridge coatings, evaluation of deterioration degree of coatings was carried out in field. According to standard for deterioration degree evaluation for steel bridge coatings used in Korea Expressway Corporation [6] shown in Table 3, 165 steel bridges were evaluated. The deterioration degree evaluation standard regulates that the bridges whose total deterioration degree score of 4 items (rust, peeling, checking and chalking) is more than 50, are regarded as the target of urgent maintenance coating. Accordingly, coating life was determined as the period that it took to reach 50 of deterioration degree score in this study.

3. Results and Discussion

3.1 Coating Life Prediction

In the accelerated weather-o-test, color difference, lightness index difference, yellowness index difference, and gloss retention were measured when every 400 h was elapsed. In both of UV-condensation and xenon-arc types, weatherabilities of fluoride resin and siloxane were superior to urethane and ceramic urethane. Evaluation results of chalking degree according to KS M ISO 4628-6 with topcoat type after 6,462 h in xenon-arc test were briefly shown in Table 4. There were a little differences with test methods and evaluation items, but relatively clear weatherability results were shown as fluoride ≥ siloxane ≫ urethane > ceramic urethane.

Regression analysis was carried out for field deterioration degree evaluation according to Table 3. According to Okamoto *et al.* [7] and Lee *et al.* [8], exponential function was used in regression analysis. Deterioration models for chlorinated rubber and inorganic zinc (IOZ)/urethane based on the field deterioration degree evaluation results were shown in Fig. 1 and Fig. 2, respectively. Regarding the time when deterioration degree score reaches 50 as life span of coatings, service lives of chlorinated rubber and IOZ / urethane system are 20.8 and 26.6 years, respectively.

Deterioration models for other coating systems that have ever been rarely used were derived by applying coordination factors for each deterioration score of rust, peeling, checking and chalking. Coordination factors were determined considering overseas study cases [1-4] and accelerated weather-o-test results as shown in Table 5. For general coating systems using inorganic zinc (IOZ) primer, coordination factors were applied to just checking and chalking related with weatherability based on deterioration model for IOZ/urethane as shown in Fig. 2, because it was thought that basic corrosion protection property was similar to IOZ/urethane system. For high performance coating system using thermal spray coating (TSC), coordination factors were applied to all the 4 items (rust,

Table 3. Evaluation criteria for deterioration degree of coatings

<table>
<tr><th>Rust</th><th>Peeling</th><th colspan="2">Checking</th><th colspan="2">Chalking</th></tr>
<tr><td rowspan="7">y=95.863-4335.723/[1+exp{(x+1.92)/0.5}]-4.85

where,
y : Score for rust
x :Area ratio of rust</td><td rowspan="7">y=75.468-691.898/[1+exp{(x+23.226)/10.38}]-8.75

where,
y : Score for peeling
x :Area ratio of peeling</td><td>Score</td><td>Condition</td><td>Score</td><td>Condition</td></tr>
<tr><td>10</td><td>Cracks wider than 1 mm exist.</td><td rowspan="2">10</td><td rowspan="2">Grade 1 in KS M 4628-6</td></tr>
<tr><td>8</td><td>Cracks narrower than 1 mm exist.</td></tr>
<tr><td>6</td><td>Visible with general corrected eyesight at a long distance</td><td>7.5</td><td>Grade 2 in KS M 4628-6</td></tr>
<tr><td>4</td><td>Visible with general corrected eyesight at a short distance</td><td>5</td><td>Grade 3 in KS M 4628-6</td></tr>
<tr><td>2</td><td>Visible with magnification of less than 10-power</td><td>2.5</td><td>Grade 4 in KS M 4628-6</td></tr>
<tr><td>0</td><td>Invisible with magnification of more than 10-power</td><td>0</td><td>Grade 5 in KS M 4628-6</td></tr>
</table>

Table 4. Evaluation results of chalking with topcoat type in xenon-arc test

Topcoat type	Urethane		Ceramic urethane		Siloxane		Fluoride resin	
Specimen	U1	U2	C1	C2	S1	S2	F1	F2
Chalking degree								
	3	2	4	4	1	1	1	1

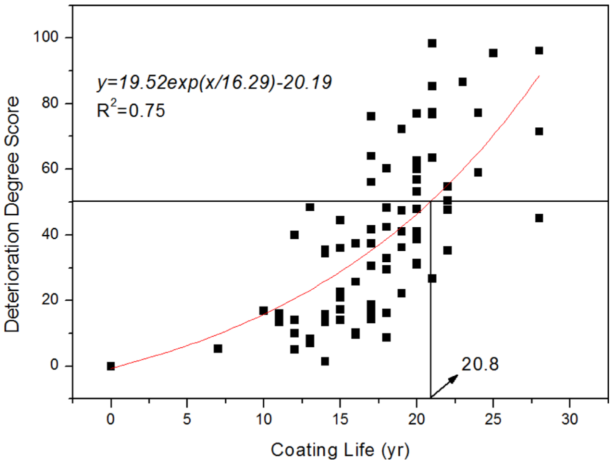

Fig. 1. Deterioration model for chlorinated rubber

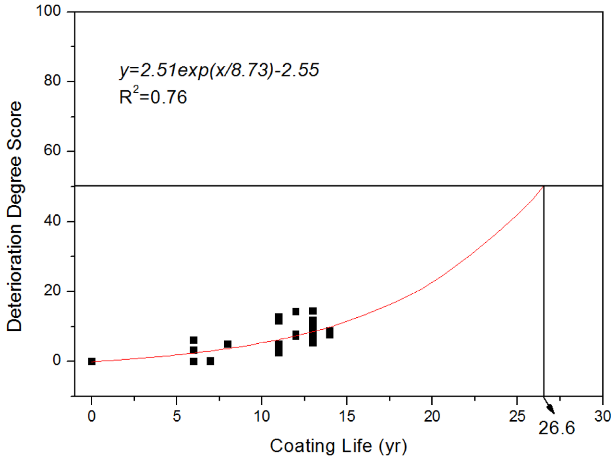

Fig. 2. Deterioration model for IOZ/urethane

Table 5. Coordination factors used for deriving deterioration models with coating systems

Coating system		Base data	Coordination factor			
Class	Topcoat type		Rust	Peeling	Checking	Chalking
General	Ceramic urethane	Deterioration degree of IOZ/urethane	1.0	1.0	1.1	1.1
	Siloxne		1.0	1.0	0.7	0.7
	Fluoride resin		1.0	1.0	0.5	0.5
High performance	Urethane	Deteriotaion degree of chlorinated rubber	0.2	0.5	0.9	0.9
	Ceramic urethane		0.2	0.5	1.0	1.0
	Siloxane		0.2	0.5	0.63	0.63
	Fluoride resin		0.2	0.5	0.45	0.45

Table 6. Predicted service lives with coating systems

Coating system		Service environment (corrosivity)		
		Severe	General	Mild
General	Chlorinated rubber	10.8	20.8	36.6
	IOZ / urethane	13.4	26.6	Semi-permanent
	IOZ / ceramic urethane	13.7	26.0	
	IOZ / siloxane	12.9	28.6	
	IOZ / fluoride resin	11.4	30.3	
High performance	Zn-Al TSC / urethane	18.2	39.4	
	Zn-Al TSC / ceramic urethane	16.6	38.9	
	Zn-Al TSC / siloxane	22.4	41.1	
	Zn-Al TSC / fluoride resin	24.7	42.2	

peeling, checking and chalking) based on deterioration model for chlorinated rubber as shown in Fig. 1. Coordination factor for rust was determined as 0.2 based on study results by U.S. Army Corps of Engineer (USACE) [4] as shown in Table 1. Coordination factor for peeling was determined as 0.5 based on the result of comparative analysis for peeling score evaluated in field. In linear regression of peeling score for chlorinated rubber and IOZ/urethane systems, peeling progress rate for chlorinated rubber system was higher as 2 times or so than for IOZ/urethane system. Coordination factors for checking and chalking of high performance coating system were determined as about 10% lower than those of general coating system, based on the results of linear regression of checking and chalking score evaluated in field for chlorinated rubber and IOZ/urethane systems. Finally, predicted service lives with coating systems calculated by above described method were shown in Table 6.

3.2 LCC Analysis

In order to select optimum economic feasible coating systems, strategies for applied coating systems should be determined. In this study, coating systems used for performance test were selected as basic strategies, and 2 types of combined coating systems were selected additionally as shown in Table 7. The combined coating systems were selected under supposition that high performance coatings were partially applied only for specific parts vulnerable to corrosion and UV.

In comparison with primer type (e.g. No. 2 and No. 3 in Table 7), coating systems using Zn/Al TSC as primer were economic feasible under severe corrosion environment, but those using conventional IOZ primer were more economic in general corrosion environment. Two types of combined cases (No. 10 and No. 11 in Table 7) were the most economic feasible because relatively long maintenance cycle could be secured with optimal cost.

LCC analysis results showed that partial application of high performance coatings to vulnerable parts could reduce LCC to maximum 50% as contrasted with conventional chlorinated rubber system, and that LCC reduction effect was higher in severe corrosion environment than in general corrosion environment.

5. Conclusions

From the case study for TSCs carried out in foreign countries, it can be find out that life of 300 μm 85/15 Zn/Al or Zn TSCs increase about 4 ~ 6 times as that of alkyd/phenolic paint coating.

In the accelerated weather-o-tests, 3 type of topcoat such as fluoride resin, siloxane, and ceramic resin showed

Table 7. LCC analysis results with coating systems

No.	Strategy		Coating Layer					LCC ratio	
			1	2	3	4	5	Severe environment	General environment
1	Chlorinated rubber		IOZ	Mist coat	Epoxy	Chlorinated rubber	Chlorinated rubber	2.02	1.64
2	Urethane topcoat	G	IOZ	Mist coat	High build epoxy	Urethane	Urethane	1.72	1.32
3		H	Zn/Al TSC	Mist coat	High build epoxy	Urethane	Urethane	1.55	1.49
4	Ceramic urethane topcoat	G	IOZ	Mist coat	Ceramic type	Ceramic urethane	Ceramic urethane	1.74	1.47
5		H	Zn/Al TSC	Mist coat	Ceramic type	Ceramic urethane	Ceramic urethane	1.70	1.58
6	Siloxane topcoat	G	IOZ	Mist coat	High build epoxy	Siloxane	Siloxane	1.75	1.28
7		H	Zn/Al TSC	Mist coat	High build epoxy	Siloxane	Siloxane	1.37	1.49
8	Fluoride resin topcoat	G	IOZ	Mist coat	High build epoxy	Fluoride resin	Fluoride resin	2.25	1.37
9		H	Zn/Al TSC	Mist coat	High build epoxy	Fluoride resin	Fluoride resin	1.37	1.57
10	Combined CASE1		Zn/Al TSC/Siloxane 10% + IOZ/Siloxane 10% + IOZ/Urethane 80%					1.08	1.00
11	Combined CASE2		Zn/Al TSC/Fluoride resin 10% + IOZ/Fluoride resin 10% + IOZ/Urethane 80%					1.00	1.01

superior performance. Chalking evaluation results showed that chalking grades of urethane, ceramic urethane, siloxane, fluoride resin were 2 ~ 3, 4, 1 and 1, respectively.

Deterioration models with coating systems were established from the results of field deterioration degree evaluation for existing coating systems. Deterioration models for other coating systems that have ever been rarely used were derived by applying coordination factors for each deterioration score of rust, peeling, checking and chalking.

From LCC analysis, partial application of TSCs for specific parts vulnerable to corrosion and UV is more advantageous than general coating systems, but application to whole steel bridge girder is not more advantageous than general coating systems under general corrosion environments. However, even whole application of TSCs is more advantageous than general coating system under severe corrosion environments. LCC analysis results showed that partial application of high performance coatings to vulnerable parts could reduce LCC to maximum 50% as contrasted with conventional chlorinated rubber system.

Up to now, high performance coatings have been rarely applied to steel bridge coatings, because cost effectiveness with coating systems was not investigated closely. It is expected that this study will contribute to widely application of high performance coatings, and service life extension of steel bridges.

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