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# Minimum Maintenance Steel Plates and Their Application Technologies for Bridge —Life Cycle Cost Reduction Technologies with Environmental Safeguards for Preserving Social Infrastructure Assets—†

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***Abstract:***

*JFE Steel has developed Ni-added high corrosion resistant weathering steels which expand the range of application of weathering steels while reducing the life cycle cost (LCC) of bridges, and a corrosion estimation technology and rust stabilization treatments as application technologies for these weathering steels. An outline of these products and technologies is presented in this paper. In the field of weathering steels, JFE Steel has developed two advanced Ni-added weathering steels which enable LCC reduction in high airborne salt environments. JFE-ACL Type 1 is a 1.5%Ni-0.3%Mo steel which considers economy while maintaining resistance to salt corrosion. JFE-ACL Type 2 is an ultra-low C-2.5%Ni steel with higher resistance to airborne salt. To support the optimum application of weathering steels in bridges, the company also developed a new software, based on voluminous exposure data, which makes it possible to estimate the thickness loss of weathering steel due to atmospheric corrosion over the lifetime of the bridge. Using this software, it is possible to propose the most suitable weathering steel for the actual bridge location. Two new surface treatment technologies which promote protective rust formation while maintaining the good appearance of bridges were also developed and commercialized. CUPTEN COAT M is a 1-coat product with excellent coatability, while e-RUS meets the need for reliable early formation of protective rust. These rust stabilizing treatments proposed by JFE Steel are environment-friendly, containing no environmental load substances such as Cr and Pb. As a additional advantage, these rust stabilizing treatments can also be applied as a primary primer using a pre-coat treatment system at the plate mill, thereby reducing coating costs.*

## 1. Introduction

The use ratio of weathering steels in steel bridges has increased rapidly, approximately tripling in the last 10 years, and now exceeds 15%[1)]. The background to this dramatic increase includes (1) social conditions which require materials that reduce the life cycle cost (LCC) of bridges and realize minimum maintenance, responding to labor shortages expected in the future due to low birthrates, and (2) progress in technologies related to weathering steels, such as the appearance of Ni-added high corrosion resistant weathering steel which can be applied in high airborne salt environments and use of rust stabilization treatments which maintain the attractive appearance of bridges while preventing rust outflow[2)].

Important considerations when judging whether

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weathering steels can be applied to a bridge or not include (a) the LCC reduction effect at the bridge construction site and (b) the effect on the environment and scenery. From these viewpoints, JFE Steel has developed Ni-added high corrosion resistant weathering steels suitable for high airborne salt environments and expanded its application technologies for weathering steels. One such technology makes it possible to predict the thickness loss due to corrosion in the actual bridge environment for both the conventional weathering steel (hereinafter referred to as JIS SMA) and Ni-added high corrosion resistant weathering steels and propose the optimum steel considering economy. Another example is JFE Steel's new rust stabilization treatment technologies which prevent rust outflow in the initial period of bridge construction in order to maintain the attractive appearance of the weathering steel bridge, and are also are compatible with the environment and offer excellent economy.

This paper describes (1) application guidelines for various types of weathering steels, which are minimum maintenance steel plates for bridges, and (2) as application technologies for these weathering steels, the features of corrosion estimation software which makes it possible to select the optimum weathering steel material and the features of the rust stabilization treatments.

## 2. Expansion of Applicable Environments for Weathering Steels

This chapter will begin by describing the LCC reduction effect when weathering steel materials are used without painting, and will then examine the applicable environments for Ni-added weathering steels in salt environments which exceed the present application guidelines for JIS SMA.

### 2.1 LCC Reduction by Weathering Steel

Weathering steel is a steel product in which the corrosion rate decreases with the passage of time because the steel has a protective property imparted by a dense layer of formed rust. This means that weathering steel can be used in structures for long periods without painting, and has the advantage of reducing maintenance costs for repainting. **Figure 1**[3] shows an example of a trial calculation of LCC for a bridge. The bridge in which JIS SMA is applied does not require paint maintenance at intervals of several years, and is economically superior to the painted bridges because maintenance and control costs can be substantially reduced.

However, weathering steel rust with a high protective property is difficult to form in high airborne salt environments. Therefore, based on a joint survey of 41 bridges throughout Japan by Public Works Research

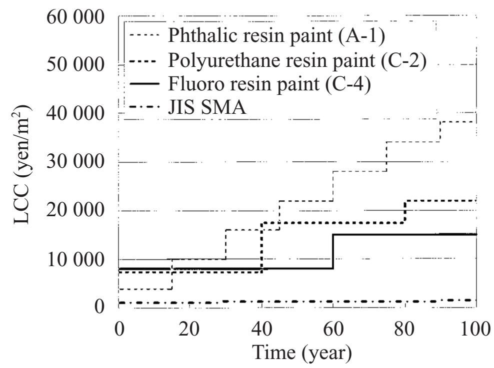



Fig. 1 Comparison of life cycle cost (LCC) of bridges with several surface treatment less than 0.05 mdd environment[3)]

Institute of the former Ministry of Construction, the Japan Iron and Steel Federation, and the Japan Association of Steel Bridge Construction, an application guideline for JIS SMA specifying use in airborne salt environments with salt concentrations of less than 0.05 mdd (NaCl: mg/dm²/day) was proposed in 1993 in Proposed Munual for Design and Construction of Unpainted Weathering Steel Bridges, Revised Version[4)]. For convenience, areas where measurement of the salt concentration can be omitted were established by distance from the shoreline.

### 2.2 Ni-added Weathering Steels

In order to respond to the distinctive topography and climate of Japan, which includes many coastlines, JFE Steel developed and commercialized two types of Ni-added weathering steels, JFE-ACL Type 1[5)] and JFE-ACL Type 2[6)], as weathering steels which have increased salt corrosion resistance in comparison with the conventional steel and can be applied in areas where the airborne salt concentration is greater than 0.05 mdd. The developed materials have the following features:

(1) Excellent corrosion resistance in environments with high airborne salt concentrations, enabling use in an unpainted condition
(2) Minimal rust outflow in the initial period, maintaining an attractive appearance
(3) Mechanical properties equivalent to those of JIS G 3114 (SMA: hot-rolled steel with weathering resistance for welded structures)
(4) Reduced C content and weld cracking sensitivity composition, securing excellent weldability and welded joint performance
(5) Availability of products suitable for a wide range of salt environments, while continuing to consider economy
(6) Possible to design bridges with excellent economy in high airborne salt areas

**Figure 2**[3)] shows an example of a trial calculation of LCC for Ni-added weathering steel bridges in a high

Table 1 Chemical compositions of Ni added weathering steels

| Steel | Thick-ness (mm) | Chemical composition (mass%) | | | | | | | | | | Mechanical properties | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | C | Si | Mn | P | S | Cu | Ni | Mo | $C_{eq}$*1 | $P_{CM}$*2 | YS ($N/mm^2$) | TS ($N/mm^2$) | El (%) | $_{V}E_0$*3, $_{V}E_{-5}$*4, (J) | $_{V}T_S$ (°C) |
| JFE-ACL400 Type1 | 12 | 0.04 | 0.30 | 0.57 | 0.032 | 0.003 | – | 1.42 | 0.30 | 0.27 | 0.13 | 291 | 460 | 34 | 373 | −59 |
| JFE-ACL490 Type1 | 50 | 0.07 | 0.32 | 0.71 | 0.033 | 0.002 | – | 1.45 | 0.32 | 0.33 | 0.16 | 358 | 515 | 38 | 281 | −43 |
| JFE-ACL570 Type1 | 75 | 0.07 | 0.26 | 0.74 | 0.029 | 0.004 | – | 1.48 | 0.31 | 0.32 | 0.16 | 532 | 625 | 32 | 270 | −50 |
| JFE-ACL400 Type2 | 50 | 0.02 | 0.27 | 0.32 | 0.011 | 0.003 | 0.37 | 2.60 | – | 0.15 | 0.10 | 355 | 460 | 40 | 355 | −35 |
| JFE-ACL490 Type2 | 50 | 0.02 | 0.29 | 0.92 | 0.006 | 0.005 | 0.37 | 2.68 | – | 0.26 | 0.14 | 445 | 528 | 39 | 388 | ≦−80 |
| JFE-ACL570 Type2 | 50 | 0.02 | 0.34 | 0.98 | 0.013 | 0.002 | 0.39 | 2.61 | – | 0.27 | 0.14 | 523 | 637 | 32 | 390 | ≦−80 |

*1 $C_{eq}$ = C + Mn/6 + Si/24 + Ni/40 + Cr/5 + Mo/4 + V/14, *2 $P_{CM}$ = C + Si/30 + Mn/20 + Cu/20 + 60/Ni + Cr/20 + Mo/15 + V/10 + 5B,
*3 ACL400 Type1, ACL490 Type1, ACL400 Type2, ACL400 Type2, ACL490 Type2, *4 ACL570 Type1, ACL570 Type2

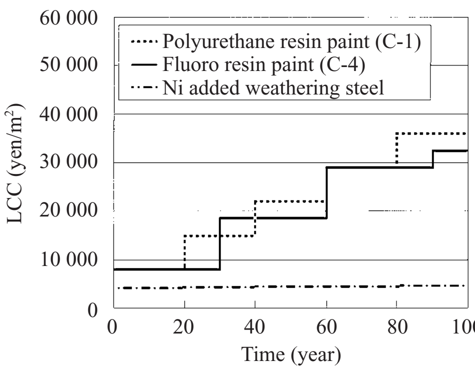



Fig. 2 Comparison of life cycle cost (LCC) of bridges with several surface treatment more than 0.05 mdd environment[3)]

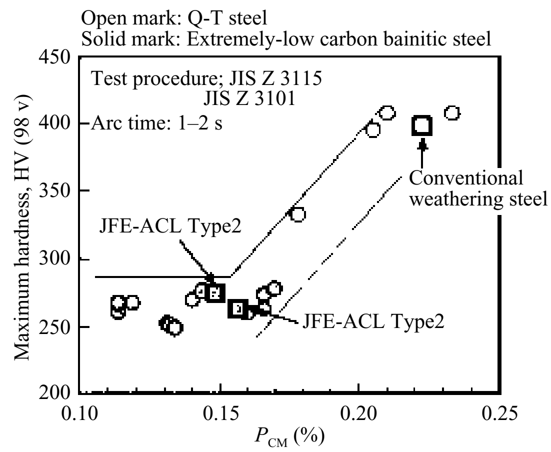



Fig. 3 Relation between $P_{CM}$ and maximum HAZ hardness of 570 MPa grade weathering steel subjected to arc strike welding[5)]

airborne salt area with a salt concentration of more than 0.05 mdd. By using Ni-added weathering steel, it was possible to design a bridge with excellent economy in an high airborne salt area where JIS SMA cannot be used.

**Table 1** shows the chemical compositions of the newly-developed Ni-added weathering steels. The standard type, JFE-ACL Type 1, which has a basic composition of 1.5%Ni-0.3%Mo features excellent economy while maintaining weathering resistance, which is achieved by a reduction in the Ni content (for cost reduction) and addition of Mo (for corrosion resistance). Ni has the effect of physically suppressing chloride ion permeability by forming a dense rust layer even in high airborne salt environments, while Mo demonstrates an effect of impeding chloride ion permeability by selective transmission of cations having an $MoO_4^{2-}$ ion. On the other hand, the high salt environment type, JFE-ACL Type 2, which has a basic composition of ultra-low C, 2.5% Ni steel displays high corrosion resistance due to its increased Ni addition. **Figure 3**[6)] shows the results of a maximum hardness test (JIS Z 3101) which was performed under arc strike welding conditions (JIS Z 3115). The material possesses excellent weldability, with a sufficiently low Vickers hardness of 275 points, due to the ultra-low carbon design.

Although these Ni-added weathering steels can be applied in high airborne salt environments exceeding the applicable range of JIS SMA (≦ 0.05 mdd), as described above, application standards for the developed steels have not been definitively established. The guideline for application of unpainted weathering steel is "estimated one-side plate thickness reduction of (0.5 mm or less)/(100 years)[7)]." Under conditions which exceed this, use of weathering steel is considered inappropriate because the plate thickness is reduced rapidly by generation of lamellar exfoliated rust. For practical reasons, it is impossible to supply products after obtaining results from a 100-year exposure test. However, Eq. (1), which was proposed by Horikawa et al.[8)], is widely used in predicting the amount of corrosion in weathering steels accompanying stabilization behavior[9)].

$$Y = A \cdot X^{B} \quad \cdots\cdots (1)$$

$X$: Exposure period (years)

$Y$: Average one-side reduction in plate thickness (mm)

$A$, $B$: Coefficient and exponent which vary depending on the environment and steel composition

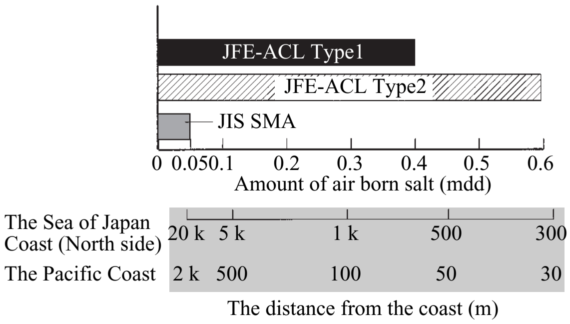



Fig. 4 Applicable area of Ni added weathering steels for coastal use

In general, unpainted weathering steel bridges display the most severe corrosion in parts where salt which has been deposited on the steel surface is not washed off by rainfall. In order to understand the corrosion behavior of severely corroded parts such as these, JFE Steel investigated the inner beams in bridges in various parts of Japan and conducted horizontal exposure tests using a covered exposure stand. Based on the results of nationwide exposure tests, which included Choshi (approximately 0.37 mdd) and Miyakojima (approximately 0.46 mdd), etc. and corrosion tests considering temperature, humidity, and salt concentration, the plate thickness reduction JFE Steel's Ni-added weathering steels (JFE-ACL Type 1 and Type 2) after 100 years was estimated based on Eq. (1) and guidelines for the airborne salt resistance of steel products were obtained. The results are shown in **Fig. 4**. From this, it can be judged that JFE-ACL Type 1 is applicable with airborne salt concentrations of 0.4 mdd or less and Type 2 is applicable with 0.6 mdd or less. For actual application, it is necessary to make a comprehensive judgment based on (1) an investigation of the bridge construction environment and (2) an investigation of bridges in the surrounding area in order to judge the corrosion environment at the bridge construction site with higher accuracy.

It may also be noted that the tendency expressed by Eq. (2)[4] was found between the concentration of sea salt and the distance from the coast.

$$C = C_1 \cdot r^{-0.6} \qquad (2)$$

$C$: Airborne salt concentration (mdd)
$C_1$: Concentration corresponding to airborne salt concentration at distance of 1 km
$r$: Distance from coast

According to Eq. (2), it can be inferred that areas with salt concentrations of 0.4 mdd or less (limit for use of JFE-ACL Type 1) account for more than 95% or all areas where JIS SMA cannot be applied (more than 0.05 mdd).

**Photo 1** shows the appearance of the Shigemisawa-bashi Bridge, in which JFE-ACL Type 1 was used (constructed in 1999, Asahi-mura, Iwafune-gun, Niigata Pref.; distance from coast: approx. 20 km). **Photo 2** shows the Shinkouji-oohashi Bridge, using JFE-ACL Type 2 (constructed in 2000, Sado City, Niigata Pref.; distance from coast: approx. 2–3 km). The appearance of both bridges is satisfactory.

Photo 1 Appearance of Shigemisawa-bashi Bridge made of Ni added weathering steel (JFE-ACL Type1)

Photo 2 Appearance of Shinkouji-oohashi Bridge made of Ni added weathering steel (JFE-ACL Type2)

## 3. Application Technologies for Weathering Steels

To enable use of weathering steels with greater confidence, an advance understanding of the formation behavior of rust is essential. In response to the greater importance attached to LCC assessments in recent years, researchers have attempted to predict the corrosion rate based on the results of exposure tests to date[10]. This chapter will describe two types of technology developed by JFE Steel: (1) a technology for estimation of long-term corrosion and (2) rust stabilization treatment technologies which preserve attractive scenic appearance while forming a dense layer of protective rust.

### 3.1 Corrosion Estimation System for Weathering Steels

It is important to determine in a simple manner the corrosion resistance method which will enable the greatest reduction in LCC in the actual construction environment and to reflect this quickly in the design of the bridge structure. As a method which meets this requirement, JFE Steel developed software for calculating corrosion of weathering steels at any desired bridge construction site in Japan using the corrosion test results discussed in section 2.2. An outline is presented below.

With this software, it is possible to reflect the influence of temperature, humidity, and the airborne salt concentration in the corrosion test results and calculate the amount of corrosion from these environmental variables. Because various environmental variables[11] for all regions of Japan are used as a database in this system, values of the environmental variables conforming to the bridge location can be set simply by inputting the bridge construction site.

**Figure 5** shows a flowchart of estimation of the change in corrosion over time. First, the location (address) where the bridge is to be constructed is set. As the temperature and humidity of this construction site, the average values for the location closest to the construction site are adopted from among approximately 160 weather bureaus nationwide. As the airborne salt concentration ($C$), the measured value at the construction site is input directly. In cases where no measured values of the airborne salt concentration are available, etc., it is also possible to calculate the value using the above-mentioned Eq. (2) by inputting the distance of the construction site from the coastline. The corrosion rate of the weathering steel is then estimated based on the airborne salt concentration. Moreover, for differences between the corrosion rate estimated by this system and the actual corrosion rate, corrosion data on actual bridges are analyzed to obtain the deviation ($\sigma$) between the estimated and actual corrosion, and this is reflected in the estimation results, resulting in improved reliability in actual application.

In order to compare long-term changes in corrosion and select materials in a simple manner, the system displays the change in corrosion over time, the range of deviation in changes, and the estimated amount of corrosion after 100 years at the construction site for JIS SMA and the Ni-added weathering steels (JFE-ACL Type 1 and Type 2). **Figure 6** shows an example of a calculation for JIS SMA and JFE-ACL Type 1 in a high airborne salt environment. With this system, the amount of long-term corrosion at any desired bridge construction site can be estimated easily, and the steel contributing to the optimum LCC reduction can be proposed, considering

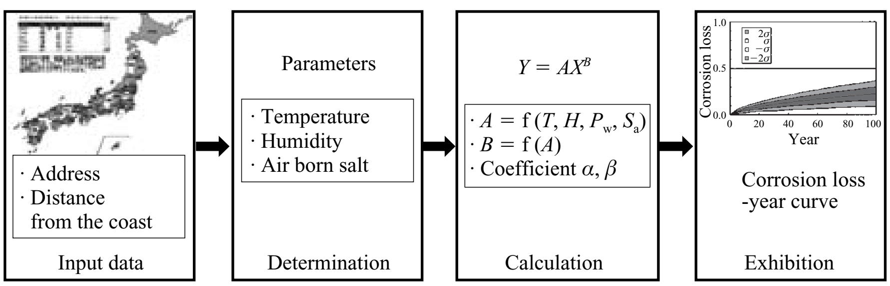
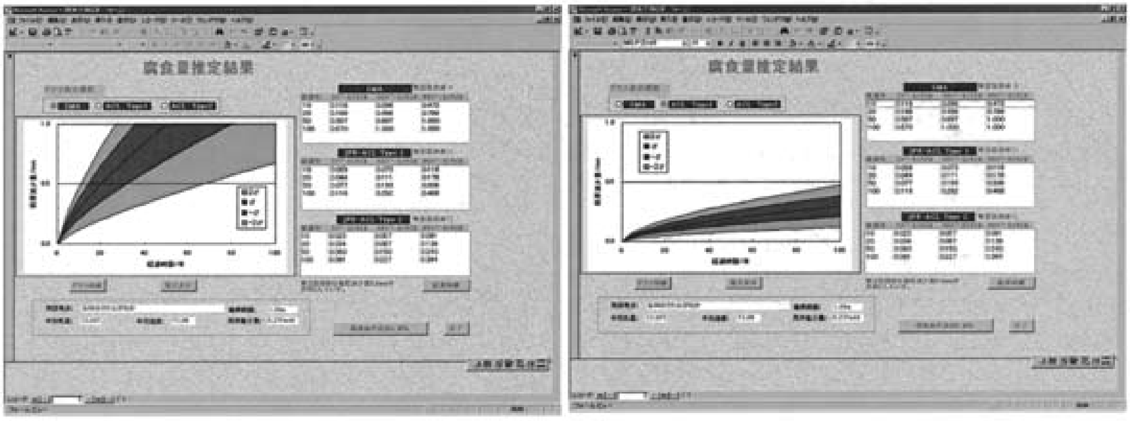



Fig. 5 Flow chart of JFE Steel's corrosion estimation system



(a) JIS SMA (b) JFE-ACL Type1

Fig. 6 Calculated curve obtained by JFE Steel's corrosion estimation system deviations in the corrosion rate.

### 3.2 Environment-friendly Rust Stabilization Treatments

Rust stabilization treatments are surface treatments which prevent changes in appearance due to rust outflow and rust color during the period until protective rust forms on weathering steels and do not require repainting. They differ from ordinary rustproof paints in that the treatment film ultimately disappears due to weathering and is replaced by the protective rust which is an essential characteristic of weathering steels. According to a survey conducted by Japan Steel Bridge Engineering Association in 2002[12], rust stabilization treatments are adopted in 44% of all weathering steel bridges, and it is considered that their use will increase in the future accompanying increasing adoption of weathering steels in urban areas.

JFE Steel developed and commercialized two new rust stabilization treatments, "CUPTEN COAT M[13]" and "e-RUS[14]," which offer a combination of the following unique JFE Steel advantages: (1) Environmental safeguards: The treatment films do not contain large environmental load substances such as Cr, Pb, and others. (2) Simple use: The treatments can be applied in the same manner as general paints for bridge use. (3) Pre-coat capability: Pre-coating at JFE Steel's works allows the customer to omit the product blasting process. JFE Steel recommends CUPTEN COAT M, which satisfies performance requirements, offers excellent coatability and economy, and has an extensive record of actual use, as a rust stabilization treatment agent. In cases where the client requires reliable formation of the protective rust film in the early period of use, the company recommends e-RUS.

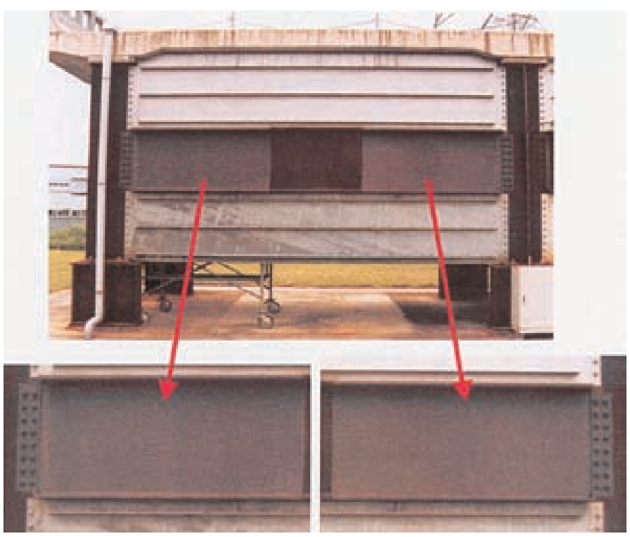

CUPTEN COAT/
JFE-ACL Type1
CUPTEN COAT M/
JFE-ACL Type1

Photo 3 Appearance of mock-up bridge treated by CUPTEN COAT and CUPTEN COAT M after 3 year-exposure in coastal area

By applying these treatment agents to Ni-added weathering steels, it is possible to prevent uneven appearance due to rust outflow and color changes, even when these steels are applied in environments with high concentrations of airborne salt. The features of these rust stabilization treatments are described in the following.

#### 3.2.1 CUPTEN COAT M

CUPTEN COAT M is a 1-layer treatment agent with excellent coatability which was developed based on knowledge gained with CUPTEN COAT (2-layer type)[15], which has a record of use in more than 700 actual bridges and has demonstrated functions of forming a protective rust film while maintaining good appearance in exposure for more than 20 years.

**Photo 3** shows the appearance of CUPTEN COAT M after exposure. Like CUPTEN COAT, which has a record of use extending over more than 20 years, CUPTEN COAT M is completely free of rust outflow and displays satisfactory appearance after exposure in terms of both color and surface condition. Moreover, because CUPTEN COAT M uses the same corrosion prevention mechanism as CUPTEN COAT, in which dense protective rust had formed after the treatment film was eliminated in exposure for 20 years[16], it is thought that dense protective rust will also form under the sound treatment film with CUPTEN COAT M as a result of long term exposure.

#### 3.2.2 e-RUS

e-RUS is an accelerating type treatment agent in which protective rust is formed reliably in the early period of use due to the addition of fine particles of artificial rust to serve as nucleation sites for protective rust in the treatment film and increases in the water and oxygen permeability of the treatment film. As a result, protective rust is formed in several years, preventing appearance defects due to local rust formation and rust outflows which occur in the early period of exposure.

**Photo 4** shows the appearance of e-RUS after exposure. No traces of rust outflow can be seen on the gypsum board which was placed under the mock-up bridge, and exposed appearance shows a transition with a satisfactory color and surface condition. When the treatment film was artificially removed with paint remover after 3 years of exposure, dense protective rust had formed over the entire surface under the treatment film, and rust outflow was also suppressed after the coating film was removed.

#### 3.2.3 Pre-coat treatment system

As an important feature of CUPTEN COAT M

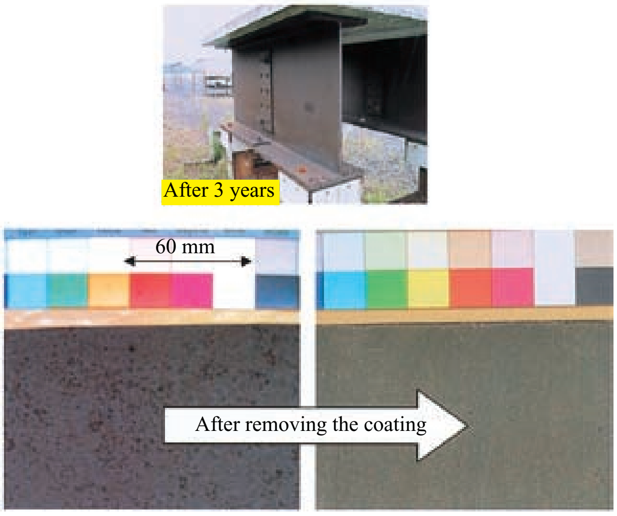



Photo 4 Appearance of mock-up bridge treated by e-RUS and rust outflow on plaster board after 3 year-exposure in coastal area

Photo 5 Appearance of World-cup-kyo Bridge applied with CUPTEN COAT M treatment and pre-coat system (Yokohama City)

Photo 6 Appearance of Maruyama-bashi Bridge applied with e-RUS treatment and pre-coat system (Okaya City)

and e-RUS, in addition to shop coating after bridge fabrication and site coating, both of these treatments can be applied as pre-coat treatments at the plate mill before the plates are shipped. **Figure 7** shows the pre-coat treatment system. As with existing primary primer treatments, pre-coat weathering steels with a thin film of rust stabilization treatment do not dirty the work site as a result of primary rust-proofing during storage and allow application of the final top coat after only simple surface preparation. **Figure 8** shows an example of the cost composition for work in conventional shop coating. Because surface preparation accounts for a large percentage of coating costs, application of the pre-coat treatment system, which makes it possible to simplify the product blasting process, can be expected to reduce coating costs.

**Photos 5** and **6** show bridges in which CUPTEN COAT M and e-RUS pre-coat treatment steel products were applied. Because a reductions in LCC and coating costs can be expected when the pre-coat treatment system is adopted, increasing use is considered probable in the future.

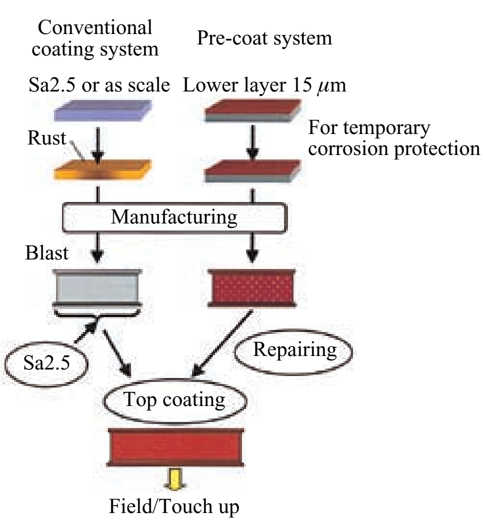



Fig. 7 Pre-coat system of new surface treatment

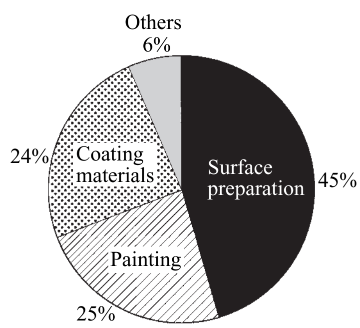



Fig. 8 Example of cost composition for conventional coating system

## 4. Conclusion

JFE Steel's weathering steels for bridges and related application technologies were described. The developed Ni-added high corrosion resistant weathering steels have high resistance to salt corrosion and provide corrosion resistance in environments with high concentrations of airborne salt exceeding 0.05 mdd, where the conventional JIS SMA could not be used, and are expected to reduce the life cycle cost (LCC) of bridges. New software using a corrosion life estimation technology makes it possible to select the optimum weathering steel material for the actual construction site at the time of bridge design. JFE Steel's rust stabilization treatments, which preserve the scenic beauty of weathering steel bridges, are both environment-friendly types, and when used together with the pre-coat treatment system, make it possible to reduce bridge coating costs. With the trend toward cost reduction in public works projects and high priority attached to LCC, weathering steels will play an increasingly large role. The developments described in this report are expected to make a large contribution to expanding the application of weathering steels not only in bridges, but also in other fields.

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