A REVIEW OF ENVIRONMENTAL FACTORS DETERMINING THE USE OF WEATHERING STEEL IN STRUCTURAL APPLICATIONS

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SUMMARY: The use of weathering steel for bridges and structural applications is highly desirable due to the potential cost savings associated with the very low atmospheric corrosion rates. The material's corrosion behaviour allows it to be used without requiring protective coatings which may be costly to maintain. Weathering steel bridges are commonly found in the US, UK and other countries but are generally not found in Australia. This paper discusses the environmental factors including airborne chlorides, atmospheric SO_2 and time-of-wetness which influence material selection and durability. Technical standards generated internationally by other road authorities are reviewed here and several criteria for selection are defined. Methods of short-term site testing during the concept design stage to determine the suitability of a potential bridge location are also discussed. In evaluating the different test methods available, consideration has been given to practicality, precision and recommended test periods.

Keywords: Weathering steel, bridges, atmospheric corrosion, materials selection, chloride

1. INTRODUCTION

Weathering steels are high strength, low alloy, weldable structural steels that possess good weather resistance in many atmospheric conditions without the need for protective coatings. They contain up to 5 wt % alloying elements, according to ASTM A242 [1], including chromium, copper and nickel. After long term atmospheric exposure, a protective rust patina forms that adheres to the surface of the steel. This layer causes the rate of corrosion to slow so that typically after 3-5 years, corrosion almost ceases [2, 3].

Avoiding the need for protective coatings has several benefits, particularly for bridges, as outlined below [4, 5]:

1. Reduced maintenance costs. Traditional steel coatings such as galvanising are not expected to last more than 50 years in most atmospheric environments. Furthermore, common barrier coatings may last up to 25 years before first maintenance. In contrast, weathering steel structures having a 100-year design life have been constructed in various countries. Such structures, where properly designed and detailed, have required relatively minimal maintenance during service. Periodic inspection and cleaning are the principal maintenance tasks.
2. Reduced initial cost. By omitting the coating operation, the overall initial cost of weathering steel bridges are often less compared the conventionally coated type. Nevertheless, these cost savings are somewhat counteracted by a potentially higher design and raw material cost.
3. Safety benefits. The reduce maintenance requirements also eliminates many safety risks encountered while conducting such tasks. Thus, weathering steel seems suited for applications such as bridges where access for coating maintenance may difficult, hazardous, or cause unacceptable traffic disruptions.
4. Environmental benefits. The environmental impact associated with emissions of volatile organic compounds (VOCs) from paint, and the containment and disposal of used blast media from future maintenance work, are avoided.
5. Distinctive appearance. A weathering steel structure with a well-developed rust patina has a unique surface colouration. It is said to begin yellow-orange then become light brown and finish chocolate to purple brown.

The formation mechanisms of the protective rust patina is well summarised in ref. [6]. Briefly, when weathering steel is manufactured, mill scale forms rapidly after hot rolling. The mill scale and initial corrosion products are porous and non-protective such that water absorbed onto the surface penetrates through to the steel. Various different corrosion products are formed initially including stable oxides and hydroxides. The structure and composition of the rust patina depends on the steel composition among various other factors. Generally, the protective scale when fully develop may be 75-80% goethite (α-FeO(OH)), with an average crystal size less than 15 nm. Multiple wet-dry cycles (either by rain or nightly condensation) over a period of years changes the nature of the corrosion products. Weathering steel develops multiple layers with the inner layer consisting of mostly dense nanophase goethite. The inner layer of nanophase goethite is highly adherent, resistant to cracking and provides a surface barrier which impedes corrosion.

The use of weathering steel bridges is prevalent in various countries including the US, UK, European nations and Japan. Although, widespread use has been observed in these countries, weathering steel bridges are generally not found in Australia.

Weathering steel bridges are known to be susceptible to premature degradation where site conditions have not be adequately considered during materials selection. One of the key requirements for the formation of the protective corrosion product layer is regular wetting and drying of the surface. Formation of the protective goethite-rich layer is inhibited by excessive times of wetness [6]. Thus, periodic drying of the moistened surface is essential to ensuring effective corrosion resistance.

Close proximity to salt laden environments or excessive exposure to other sources of chlorides is also undesirable for long-term performance. High chloride levels may cause the formation of akaganeite (β-FeO(OH)) in preference to goethite also reducing the corrosion resistance [6]. High sulphide or sulphate environments may also impair the protective layer. For example, severe air pollution may generate localised areas of high acidity and dissolve the protective layer [6]. Thus, the ideal exposure condition for weathering steel is one where the surface is washed frequently to remove contaminants but can also be dried by the sun.

The paper seeks to discuss the key environmental factors which influence material selection and durability of weathering steel bridges in Australia. Technical standards generated by international road authorities are reviewed here and the criteria for selection are defined and quantified. This paper further considers some of the methods of site testing to determine the suitability of a proposed bridge site. Discussions shall be limited to the design considerations and environment factors concerning concept design (sometimes termed front-end engineering design). Brief comments pertaining to aspects of detailed design are made however further discussion has been excluded from this paper.

2. EXISTING GUIDANCE FOR MATERIALS SELECTION

To evaluate the suitability of weathering steel in an Australian context, three general sources of guidance were reviewed, namely 1) UK standards, 2) US standards and 3) ASTM standards and long-term data.

2.1 UK Standards

The UK Department of Transport, Design Manual for Road and Bridges [7] contains instructions on situations where the use of weathering steel is not suitable. The standard has been well summarised below [8]:

Restrictions on use

Weather resistant steel is not suitable for the following environments:

- *where there is an atmosphere of concentrated corrosive or industrial fumes. This may be defined as having a pollution classification above P3 to ISO 9223 ($SO_2 > 250\ \mu g/m^3$ or 200 mg/m^2 per day).*
- *where steel is exposed to high concentrations of chloride ions or salt spray. (This may be defined as an environment having a salinity classification greater than S2 to ISO 9223 (Cl > 300 mg/m^2 per day). Caution is therefore needed when considering use within 2 km of a coast.*
- *where the headroom to steel over water is less than 2.5 m.*

The P3 classification ("highly polluted industrial atmosphere") is the highest category in ISO9223 [9]. An S2 classification is the second highest category where airborne chlorides are determined by the wet candle method specified in ISO9225 [10].

The UK standard also contains recommendations for the corrosion allowance for bridges designed in accordance with BS5400. That is, bridges having a design life of 100 years.

Loss of section

- *Allowance should be made for the formation of rust and the resultant loss of structural section over the life of the bridge.*
- *The thickness lost depends on the severity of the environment, and the following allowances for this loss are recommended:*

Atmospheric Corrosion Classification (ISO 9223)	Weathering Steel Environmental Classification	Thickness Allowance on each exposed face
C1, C2, C3	Mild	1.0 mm
C4, C5	Severe	1.5 mm

- *Interior faces of ventilated boxes: allow 0.5 mm.*
- *Interior faces of sealed boxes: no allowance needed.*

The suggested corrosion allowances for a C4 and C5 environment are somewhat redundant in typical Australian conditions. This is because a C4 and C5 environment typically exceeds the allowable chloride deposition rate of 300 $mg/m^2/day$ outlined above [9]. Thus, weathering steel should not be used in a C4 or C5 environment and requires careful evaluation in a C3 environment.

2.2 ASTM G101

ASTM G101 [11] provides guidance for selecting an appropriate corrosion allowance for weathering steel. One method involves extrapolating thickness loss values taken from short term testing. Examples are provided including studies on two different grades of weathering steel in a marine environment (Figure 1).

The thickness loss values found in ASTM G101 have been collected over 15 years and extrapolated to 100 years. At the sites shown in Figure 1, the thickness losses were all predicted to be less than 1000 µm after 100 years. As a reference, the US site shown in Figure 1 is Kure Beach, 250 metres from the beach. This site may be classed as having a C3 atmospheric corrosivity (based on carbon steel corroding at a rate of 40 µm/year). Over a 30 year period, the average chloride deposition rate at this site was determined to be 100 $mg/m^2/day$ [12]. The weathering steels test panel are said to be performing satisfactorily in this location [6].

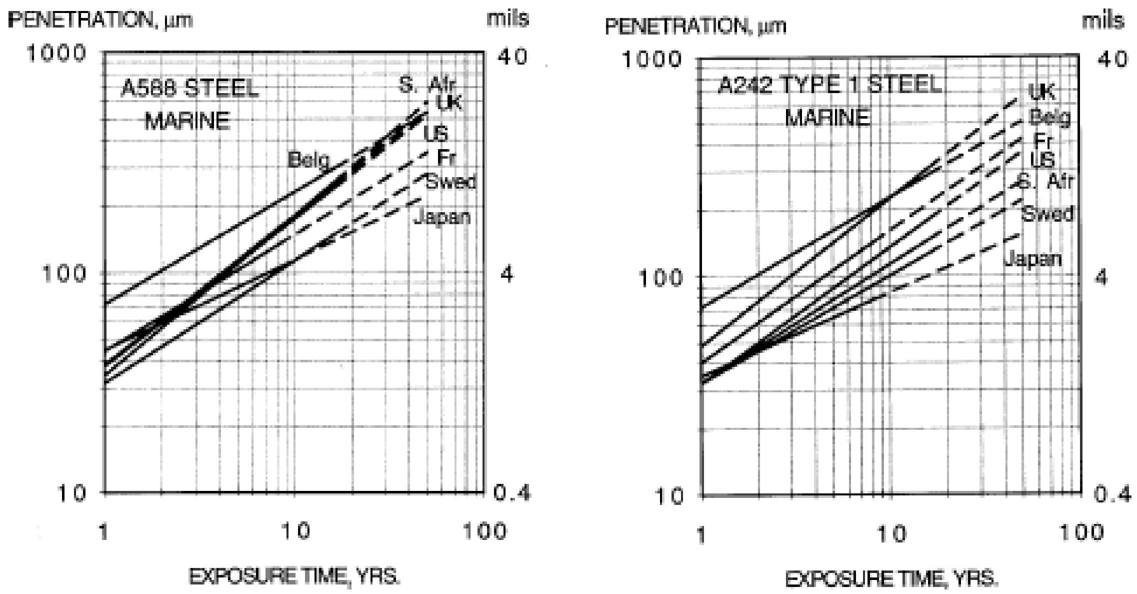

Figure 1 Projected thickness loss per surface for two weathering steel grades in a C3 marine environment [11]

The projected weathering steel thickness loss shown above seems to confirm the corrosion allowances recommended in UK standards are sufficient for a C3 category (i.e. 1.0 mm).

ASTM G101 also provides an indication of the relative influence of temperature on the corrosion behaviour of weathering steel. In C3 marine environment, there is a poor correlation between the average temperature and the rate of thickness loss. Furthermore, the two warmest test sites shown in Figure 1 (Kure Beach, US and Kwa Zulu Coast, South Africa) had relatively moderate corrosion rates. These locations had an annual average temperature of approximately 18°C. This indicates that there are factors other than temperature that have a more significant influence on the corrosion behaviour of weathering steel.

2.3 ASM Handbooks and US Federal Highway Technical Advisory

While not intended to be used as prescriptive guide for design or materials selection, ASM Handbook Vol 13B [6] and the Federal Highway Technical Advisory [13] are highly informative through their review a several of long-term studies. They note that weathering steels are not suitable for environments where the chloride deposition rate exceeds 50 $mg/m^2/day$. This is a more conservative value than that suggested by the UK standard (300 $mg/m^2/day$).

Similarly, they note that weathering steels should not be used where the average SO_3 deposition rate exceeds 210 $mg/m^2/day$.

ASM Handbook [6] also recommends that weathering steels are not to be used when the annual average 'time-of-wetness' exceeds 60%. According to ISO9223 [9], the 'time-of-wetness' is defined as the duration where the relative humidity exceeds 80%. Thus, weathering steels should not be used in locations where the relative humidity exceeds 80% for more than 220 days (or 5300 hours) a year.

2.4 Summary of Standards

There are three main parameters which may restrict the use of weathering steels in any given atmospheric environment. A summary of the guidance provided in the literature on the suitable use of weather steel is provided in Table 1.

Table 1: Summary of environmental factors where weathering steels are suitable. The most stringent requirements are shaded.

	Airborne Chloride Levels	SO_2 Levels	Time-of-Wetness*
UK Standards and Literature	Less than 300 $mg/m^2/day$ and greater than 2 km from the coast	SO_2 less than 250 $\mu g/m^s$ or 200 $mg/m^2/day$	*Steel must be located more than 2.5 m above water*
ASTM G101 and long term test data	*Satisfactory performance after long term exposure to 100 $mg/m^2/day$, 250 m from the beach*	-	-
US Standards and Literature	less than 50 $mg/m^2/day$	SO_3 less than 210$mg/m^2/day$	Less than 60% TOW*

(*) Time-of-Wetness is the duration where the relative humidity exceeds 80%.

By way of comparison, at Kure Beach (NC, USA), test sites at distances 25 and 250 m from the ocean had average chloride deposition rates measured over 30 years of ~400 and ~100 $mg/m^2/day$, respectively [12, 14]. In Townsville (QLD, Australia), a test site 1.5 km from the ocean measured chloride deposition rates between 15 and 25 $mg/m^2/day$ over a 12 month period [15]. As noted above, published chloride deposition rates taken at Australian locations are rare.

3. OPTIONS FOR SITE EVALUATION DURING CONCEPT DESIGN STAGE

Determining whether a potential site for future construction is suitable for the use of weathering steel is challenging, particularly during or prior to the concept design stage. The inherently short timeframes imposed on projects create an additional challenge to evaluating the environmental factors at any potential site. Furthermore, since weathering steel structures are not commonly found in Australia, it is difficult to evaluate the suitability of any given site by comparing the performance of weathering steel at another nearby location having similar or higher corrosivity. Nevertheless, the potential options for determining chloride deposition rates, atmospheric SO_2 levels and time-of-wetness valuation are reviewed below.

3.1 Airborne Chloride Deposition Rate

The standard technique and seemingly most accurate method for determining chloride deposition rates is via the 'wet candle' technique. This is well described in ISO9225 Annex D [10] and has been used in the standards and long-term studies discussed above. Briefly, the wet candle apparatus consists of a wick inserted into a bottle of liquid. Liquid is drawn up the wick to an exposed section having a known area. Airborne chlorides carried by wind impinge on the wick and are absorbed into the liquid. The apparatus must be exposed to the wind while also being sheltered from rain. After a certain test period, the amount of chlorides collected is determined by chemical analysis and a chloride deposition rate is calculated.

According to ISO9225, the preferred minimum test period is one year as this enables factoring of seasonal variations. Such a test period is typically unacceptable during most concept design stages of projects. Furthermore, the assembly of a wet candle apparatus and shelter is not trivial. A suitable test location protected from vandalism and near the proposed project site is also often not available. Thus, conducting a project-specific wet candle test does not appear suited during concept design. The high precision and long test periods associated with the technique seems better suited for corrosion research where high experimental care and rigor is possible.

There is a relatively limited amount published data from wet candle testing at sites around Australia [15]. Available data collected by CSIRO and Standards Australia has been used to generate various corrosivity maps such as those found in AS4312 [16] as well as the Ingal-CSIRO Corrosion Mapping System available for public use [17]. The Ingal-CSIRO Corrosion Mapping System appears to calculate the chloride deposition rate at any given location primarily using its proximity to the coast. An example screenshot is shown in Figure 2. The information provided by this system may be regarded indicative as various geographical and other factors are likely not considered. Nevertheless, the Ingal-CSIRO Corrosion Mapping System seems a simple means of obtaining an indicative chloride deposition rate and may be sufficient in most cases during concept design.

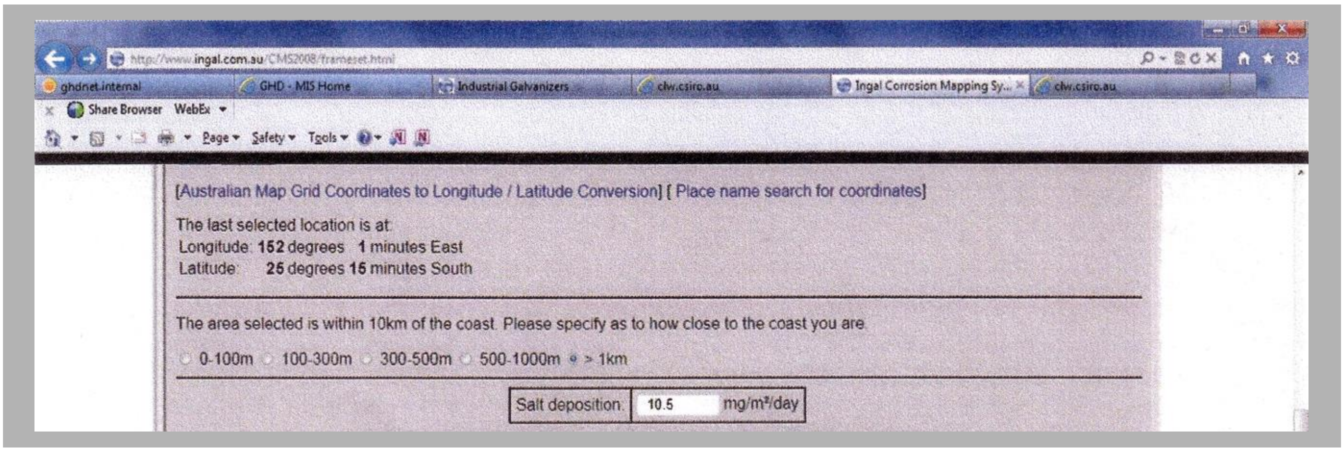

Figure 2 Example screenshot of Ingal-CSIRO Corrosion Mapping System [17].

At locations where there may be a lack of published data or where corrosion mapping systems are not reliable (e.g. close to coast but relatively sheltered), it may be necessary to conduct short term site testing to determine actual chloride deposition rates. An alternative to wet candle technique is the dry plate method, as described in ISO9225 Annex E [10], where chlorides deposited on a dry, gauze substrate are collected after a test period for chemical analysis.

Another alternative technique, suggested here, is to use the Bresle Test method. The test technique is described in ISO8502-6 [18] and is normally used for the testing of surface chlorides prior to blasting and painting. Briefly, metal surfaces for testing are covered with a specially made test patch which creates a 'pocket' with a controlled area on the test surface. Deionized water of known volume is injected into the pocket dissolving any soluble salts present on the surface (Figure 3). After some mixing and interaction within the pocket, the fluid is extracted and the conductivity measured using a handheld meter. The correlation between conductivity and the concentration of salt has been published in CRC Handbook of Chemistry and Physics [19]. If it is assumed that the only contribution to conductivity is from dissolved salt deposits, an upper bound estimate of surface chloride concentration can be obtained. In reality, other deposits such as conductive fines and sulphides will contribute to the conductivity of the extracted solution.

Figure 3 Bresle test method. Image taken from public domain.

To obtain an average chloride deposition rate, appropriate test surfaces must be selected. These are preferably non-porous, sheltered from rain as well as upright and facing on-shore winds. Initially, the test surfaces should be cleaned thoroughly, preferably using a high pressure water blast, then rinsed with distilled water. Over time chlorides will accumulate on the cleaned surface. Multiple Bresle tests should be conducted weekly over a period of a few month at spots over the washed surface to determine the change in surface chloride concentration over time. The chloride deposition rate may then be evaluated and compared to the guidance provided in the standards above.

According to ISO9225 Annex F [10], chloride deposition rates measured by the wet candle technique are 2.4 times greater than that determined by techniques using dry surfaces. Thus, values obtained by the the dry plate method or Bresle test technique must be multiplied by this correction factor to allow appropriate comparisons. The incorporation of a scaling factor is possibly due to a reduced level of retention of airborne chlorides on a dry surface compared to a wet.

When determining the chloride deposition rate during concept design, there are two key advantages of applying the Bresle test method over the wet candle and the dry plate method.

1. A Bresle test can be conducted on any non-porous surface. Thus, chloride deposition rates can be determined using existing structures and surfaces at or near proposed project sites. This avoids the need for installing special shelters to protect apparatus. Sheltered locations at stations, bus stops and public parks may provide suitable test surfaces.

2. By avoiding the need for laboratory chemical analysis and sampling, the test process is relative simple and cost effective. Due to their prominence in the coatings industry, Bresle test kits are widely available allowing technicians to mobilise quickly and obtain data immediately from the field.

However, for trustworthy results to be obtained and a proper assessment of the site to be conducted, some of the following measures should be taken:

1. Chloride deposition rates are known to change with seasons [12]. Thus, the evaluation of a proposed site in a short time period necessitates that testing be conducted during seasons of typically high on-shore winds. This may be determined from historical meteorological data.

2. Since the Bresle test measures the accumulation of surface chlorides over time, care must be taken initially to ensure that the surfaces are properly cleaned. An initial Bresle test should be conducted immediately after cleaning to determine the 'zero' surface chloride concentration. It is also important that the surface remained unwashed over the test period either by rain or even unknowingly during routine cleaning by maintenance personnel.

3. It is important that the surfaces selected for testing are non-porous, upright and facing on-shore winds. This is to ensure the chlorides transported in the wind are properly sampled by the selected surface. Soffits and roof surfaces are not suitable.

Should the above measures be employed, an upper bound estimate of the airborne chloride deposition rate may be determined after 5 to 10 weeks. Figure 4 is an example of a suitable test surface encountered in the field. The horizontal member at the public bus stop is recessed beneath the roof and thus sheltered from rain. The painted surface is also intact and facing the ocean.

Figure 4 Example test surface (circled) suitable for chloride deposition rate testing via the Bresle method.

3.2 Atmospheric Sulphur Dioxide

Atmospheric SO_2 is predominantly a concern at locations downwind from certain types of industry or where there is heavy traffic pollution. According to AS4312 [16], a C4 corrosivity zone may "*be found inside large industrial plants with steam production, and perhaps up to 1.5 kilometres downwind of the plant*". The use of weathering steel at a proposed project location may be assessed in a few ways. Unlike airborne chloride deposition rates, historical SO_2 data is typically unreliable due to inherent variations in industrial emissions. Published historical data, less than a few years old, may be available. However, these are typically government air monitor studies which only include a few locations of interest.

The standard techniques for measuring atmospheric SO_2 is described in ISO9225 Annex A, B and C [10]. The basic principal involves preparing an apparatus where SO_2 gas will be absorbed by a reactive substrate consisting of either lead dioxide (PbO_2) or an alkaline solution (e.g. Na_2CO_3 or K_2CO_3). However, unlike testing for chloride deposition rates, commercially available SO_2 test kits employing similar principals have been developed. An example apparatus is shown in Figure 5.

Figure 5 Example of commercially available SO_2 sampling system.

Some of these commercially available test kits appear to have a very high sensitivity to SO_2 gas potentially allowing precise SO_2 sampling in a short period. This seems well suited to the short time frames imposed during concept design. However, one of the disadvantages with a highly sensitive device is also a higher susceptible to contamination. Contamination may occur during testing and handling. However, it is also recommended that control samples are tested before any site testing begins to ensure all SO_2 samplers are not contaminated during manufacture and that a valid result will be obtained after the test period.

The techniques for measuring atmospheric SO_2 described in ISO9225 will provide a deposition rate (in $mg/m^2/day$) while some of the commercially available test kits will determine the concentration of atmospheric SO_2 gas (in $\mu g/m^3$). According to the UK standard for weathering steel use, both values can be used to evaluate the suitability of a proposed location.

3.3 Time-of-Wetness

Infrequent washing of the surface by rain is beneficial for corrosion resistance, whereas, excessive periods of wetness or the pooling of water on the surface does not allow a protective rust patina to form. The standard method of determining time-of-wetness is described in ASTM G84-89 [20]. However, according to ISO9223, the length of time during which the relative humidity is greater than 80% may be used to estimate the time-of-wetness. Published meteorology data taken from weather stations located around Australia seems the most accessible source during concept design. Should reliable data be unavailable, site testing also seems relatively simple. A weather station may be installed at a site and the local humidity logged. Ideally, the weather station should be installed at an identical height above ground as the proposed bridge or structure.

4. KEYS ASPECTS OF DETAILED DESIGN

There are several guidance documents discussing the various aspects of detailed design which affect durability [4, 5, 7, 8]. These aspects have not been discussed here but may include:

- Surface preparation requirements
- Welding procedures and consumables

- Control of drainage and crevices
- Storage and transportation requirements during shipping
- Control of run-off of corrosion products
- Use of dissimilar metals in construction and welding practices.
- Control of surfaces exposed to environmental washing by rain

There are also stringent requirements on bolted faces, identification markings on the steel, inspection, monitoring, maintenance, and vegetation control.

5. CONCLUSIONS

The use of weathering steel offers several advantages over conventionally coated or galvanised structural steel. The very slow corrosion rate allows the material to be used uncoated, minimising maintenance requirements. Although weathering steel bridges and structures are commonly found in other countries, its use in Australia is relatively limited. Standards from the US and UK, as well as published literature, outline criteria based on three main environmental factors, namely, chloride deposition rates, atmospheric SO_2 and time-of-wetness which can be reasonably applied to Australia. Based on these, weathering steel in Australia should not be used in a C4 or C5 environment while careful evaluation is required in a C3 environment.

Specifically, weathering steel should not be used at locations less than 2 km from the coast or where the chloride deposition rate exceeds 50 mg/m^2/day. In an industrial location, it should not be used where SO_2 levels exceed 250 $\mu g/m^3$ or 200 mg/m^2/day. These above requirements are due to the effects of chlorides and sulphur compounds which prevent the protective rust patina from forming.

Cyclic wetting and drying of the weathering steel surface is another important requirement for forming a protective patina. Thus, the material should not be used without a clearance of 2.5 m above the water level or at locations where the relative humidity exceeds 80% for longer than 60% of the year.

Evaluating the above environmental factors is a significant challenge during the concept design stage due to the typically short time frames imposed. A practical means of evaluating the chloride deposition rate at a proposed location includes the dry plate method and the Bresle test method. An indicative value may also be obtained from the Ingal-CSIRO Corrosion Mapping System. To evaluate SO_2 levels, commercially available SO_2 samplers have also been developed and appear the most practical for site testing. Finally, published meteorology data taken from nearby weather stations may be used to evaluate the time-of-wetness.

Within these guidelines, there seems to be no reason for weathering steel not to be used for bridges and structures in Australia. Where a suitable location has been identified, the above standards stipulate a minimum 1.0 mm corrosion allowance should be nominated for structures having a 100-year design life.

6. ACKNOWLEDGMENTS

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