ATMOSPHERIC CORROSION DATA OF WEATHERING STEELS. A REVIEW.

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ABSTRACT

Extensive information on the atmospheric corrosion of weathering steel has been published in the scientific literature. The contribution of the present work is to provide a bibliographic review of the reported information, which mostly concerns the weathering steel ASTM A-242. This review addresses issues such as rust layer stabilisation times, steady-state steel corrosion rates, and situations where the use of unpainted weathering steel is feasible. It also analyses the effect of exposure conditions. Finally it approaches the important matter of predicting the long-term behaviour of weathering steel reviewing the different prediction models published in the literature.

Keywords: A. Low alloy steel; C. Atmospheric corrosion; C. Rust

1.   Introduction

Weathering steels (WS), also known as low-alloy steels, are steels with a carbon content of less than 0.2 wt. % to which mainly Cu, Cr, Ni, P, Si and Mn are added as alloying elements to a total of no more than 3-5 wt. % [1]. The enhanced corrosion resistance of WS in relation to mild steel or plain carbon steel (CS) is due to the formation in low aggressive atmospheres of a compact and well-adhering corrosion product layer known as patina.

This definition, however, has not remained unchanged but has evolved as new WS compositions have been developed to achieve improved mechanical properties and/or withstand increasingly aggressive atmospheric conditions from the corrosion point of view, especially in marine environments. The American Society for Testing and Materials (ASTM) has standardised different alloy compositions for WS, from an initial 1.5% total weight of alloying elements added in the first standardised WS A-242 [2], to 5% in the last standardised WS A 709-HPS 100W [3], which is at the limit of the composition of intermediate alloy steels. Table 1 sets out the chemical composition of two commonly used WS [2, 4].

The patina on WS not only offers greater corrosion resistance than on mild steel, but is also responsible for its attractive appearance and self-healing abilities. The main applications for WS include civil structures such as bridges and other load-bearing structures, road installations, electricity posts, utility towers, guide rails, ornamental sculptures, façades, roofing, etc.

The literature contains a great deal of information on WS, and there are entire chapters in collective works dedicated to this issue, e.g. [1, 5-6]. However, an in-depth bibliographic

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review on the atmospheric exposure data of WS and a rigorous analysis of the published information are lacking. The review presented in this paper seeks to fill this gap.

2.　　Brief historical development

Albrecht and Hall [7] published a complete review on the historical development of WS.

The birth of WS can be traced back to the development of steels containing copper, known as copper steels [8]. In 1910 Buck observed that steel sheets with 0.07% Cu manufactured by US Steel and exposed in three environments of different corrositivities (rural, industrial and marine) showed a 1.5-2% greater atmospheric corrosion resistance than CS [9]. Hence, in 1911 US Steel started to market steel sheets with a certain copper content. Buck subsequently reported that the improvement achieved with Cu concentrations in excess of 0.25% was insignificant, noting that 0.15% Cu provided similar results to 0.25% Cu in most cases [10].

Once this capacity of copper steel became known, further research led to the development of WS and thus to High Strength Low Alloy (HSLA) steels [7]. In the 1920's US Steel produced a new family of HSLA steels intended primarily for the railway industry. Finally, in 1933 US Steel launched the first commercial WS under the brand name USS Cor-Ten steel (Early Cor-Ten steel or Cor-Ten B), a name which reflects the two properties that differentiate it from CS, i.e. its corrosion resistance (Cor); and from a copper steel, i.e. its superior mechanical properties (tensile strength, Ten). This product was claimed to provide a 30% improvement on the mechanical properties of conventional CS, thus reducing the necessary thickness and accordingly the weight of steel to be used for a given set of mechanical requirements [11]. Figure 1 illustrates the corrosion of these three steels in the industrial atmosphere of Kearny and its evolution with time [12]. Attention is drawn to the lower corrosion experienced by the Early Cor-Ten steel.

Early versions of USS Cor-Ten steels were based on Fe-Cu-Cr-P systems, to which Ni was later added in order to improve corrosion resistance in marine environments. USS Cor-Ten steels presented two specifications, A and B, whose main difference lay in the amount of phosphorus present in their composition. USS Cor-Ten A can be said to be the WS with the highest phosphorus content (0.07-0.15% weight) and USS Cor-Ten B that with the lowest phosphorus content (≤0.04 % weight) [13].

Greater knowledge of the role played by the different alloying elements (Cu, Cr, Ni, P, etc.) in the atmospheric behaviour of WS was achieved thanks to two ambitious studies carried out in the United States, one began in 1941 by ASTM Committee A-5 [14] and another began in 1942 by US Steel Co. [12]. In the first, 71 low-alloy steels were exposed to the industrial atmosphere at Bayonne, N.J. and to the marine atmospheres at Block Island, R.I. and at Kure Beach (250 m), N.C. In the second study, 270 different steels were exposed in the following atmospheres: South Bend, Pa (semi-rural), Kearny, N.J. (industrial) and Kure Beach (250 m), N.C. (marine).

The current composition of USS Cor-Ten steels has altered to a certain extent, especially in the case of specification B, with the addition of Ni (≤0.40 % Ni), but they all continue to be marketed to the present day [15-16]. In 1941 the first WS was standardised by ASTM specification A-242; a steel that is roughly comparable to USS Cor-Ten A steel. Its main characteristic is its high resistance to atmospheric corrosion, which is approximately 4 times greater than that of CS due to the presence of copper, a high phosphorus content, and in

general the presence of nickel (0.50-0.65%). However, it is now somewhat obsolete as a structural steel due to the fact that phosphorus can form iron phosphide (FeP_3) during the welding process, decreasing its weldability and causing the steel to become brittle.

In 1968 ASTM standard A-242 presented two specifications, one with a high phosphorus content (<0.15% P) and the other with a lower phosphorus content (<0.04% P). The latter was ultimately replaced by ASTM standard A-588 WS [4] (see Table 1), which is roughly comparable to USS Cor-Ten B steel. This steel possesses less resistance to atmospheric corrosion due to its lower P content, but for this same reason it has better weldability.

Finally, in 1992 the US Federal Highway Administration (FHWA), the American Iron and Steel Institute (AISI) and the US Navy started to develop new improved WS for bridge building, known as High Performance Steels (HPS), and in 1997 the first bridge with HPS-70W was built in Nebraska [17]. Three basic targets were set to improve the overall quality and manufacturability of the steels used hitherto for bridge construction in the United States [18]: (a) improve weldability, achieved by lowering the carbon, phosphorus and sulphur contents; (b) improve mechanical properties, such as fracture toughness and yield strength, achieved by raising the maximum manganese limit; and (c) maintain the formation of protective rust that characterises WS.

3.   Requirements for the formation of protective rust layers on WS

As has been mentioned, the enhanced corrosion resistance of WS is due to the formation of a dense and well-adhering corrosion product layer.

Experiments carried out in 1969 by Schmitt and Gallagher with low alloy steel (Cor-Ten A) indicated that the texture of the oxide layer was dependent upon the washing action of rainwater and the drying action of the sun [19]. Surfaces sheltered from the sun and rain tended to form a loose and non-compact oxide while surfaces openly exposed to the sun and rain produced strongly adherent layers. On north-facing surfaces the protective layer developed somewhat more slowly as a result of receiving less sunlight. Matsushima et al. [20] subsequently studied the role of a large number of environmental and design variables in the behaviour of WS in architectural applications, verifying the decisive influence on the formation of the protective patina of whether or not the metallic surface was exposed to the rain, or whether or not areas where moisture was liable to accumulate were drained. These effects were more intense in atmospheres with higher pollution levels, in which case the protective patina may not fully form.

Extensive research work has thrown light on the requisites for the protective rust layer to form. It is now well accepted that wet/dry cycling is necessary to form a dense and adherent rust layer, with rainwater washing the steel surface well, accumulated moisture draining easily, and a fast drying action (absence of very long wetness times). Structures should be free of interstices, crevices, cavities and other places where water can collect, as corrosion would progress without the formation of a protective patina. It is also not advisable to use bare WS in continuously moist exposure conditions or in marine atmospheres where the protective patina does not form [5-6, 21].

Therefore, the ability of weathering type steels to fully develop their anticorrosive action is dependent on the climate and exposure conditions of the metallic surface. It must also be

taken into account that a truly protective oxide film may never develop on certain areas, or that their evolution will be excessively slow.

4.   Atmospheric corrosion data of WS. Worldwide survey.

Over the years, the first extensive field tests of WS carried out by Copson [14] and Larrabee-Coburn [12] have been followed by further studies all over the world.

A worldwide literature survey has been conducted to obtain data series on WS corrosion versus exposure time [14, 22-55]. Table 2 lists the countries and testing stations where atmospheric exposure studies have been undertaken, as well as some general characteristics of the tests performed.

A factor of uncertainty is that the atmospheres are often classified in purely qualitative terms as rural, urban, industrial or marine, based on subjective assessments of pollution factors. It can also be seen that large amounts of data are available for behaviour in the first 10 years of exposure, but there is notably less information on long-term exposure for more than 20 years.

The bulk of the data refers to ASTM A-242 WS, and as such this is the steel which is particularly referred to throughout this review.

The abundant literature on atmospheric corrosion of weathering steels can sometimes be confusing and lack clear criteria regarding certain concepts that are addressed in the present paper, namely:

(i)   How long does it take to reach a steady state (stabilisation of the rust layer) in which the corrosion rate remains practically constant?

(ii)   Effect of environmental exposure conditions

(iii)   What laws best fit the atmospheric corrosion of WS and estimation (prediction) of long-term atmospheric corrosion?

Each of these issues is addressed below.

5.   Stabilisation of rust layers and steady-state corrosion rate

Bibliographic information on this aspect is highly erratic and variable, going from claims that a protective patina can be seen to be formed after as little as 6 weeks exposure to reports of stabilisation times of one year, 2-3 years, 8 years, and so forth [56].

Matsushima et al. [20] reported the time required for the corrosion product to stabilise according to its location in the structure and whether the environment was industrial or urban. This time varied from 1 to 5 years, except for locations where stabilisation did not occur due to water pool formation.

The gradual development of a protective layer on WS takes several years before steady-state conditions are obtained. The time taken to reach a steady state of atmospheric corrosion will obviously depend on the environmental conditions of the atmosphere where the steel is exposed.

To determine the stabilisation times of rust layers formed on WS in the different atmospheres, reference has been made to information obtained in the aforementioned bibliographic survey (Table 2). Prior to its analysis the database has been refined by removing all data series which

have information for only a small number of points (e.g. 1 or 2 points on corrosion rate versus time curves), which correspond to studies that ended after short exposure times (<7 years), or in which it was not possible to determine the stabilisation time due to rising corrosion rates with exposure time, excessively high corrosion rates, etc.

The procedure established to determine rust layer stabilisation times and steady-state corrosion rates has been as follows:

1. The available corrosion rate, y, is plotted against the exposure time, t_1, and fitted to an exponential decrease equation:

$$y = A_1 \exp\left(\frac{-x}{t_1}\right) + y_O \qquad (1)$$

2. Once the equation (1) is obtained, it is used to determine the corrosion rate at different exposure times and to calculate the decrease in the corrosion rate for each annual increment in exposure.

3. A steady state (stabilisation time) is considered to have been reached when the decrease in the corrosion rate for a one-year increment in exposure time is $\leq 10\%$. (Fig. 2).

4. The steady state corrosion rate is the rate corresponding to the year from which a decrease of $\leq 10\%$ takes place (Fig. 2).

With the information selected in this way, tables 3 and 4 have been prepared for non-marine (rural, urban and industrial) and marine atmospheres respectively, listing the testing stations in order of corrosivity categories according to ISO 9223 [57], obtained from corrosion data for CS after one year of exposure.

The tables contain the following information: ISO corrosivity category (ISO 9223), site and country, first-year CS corrosion (μm), stabilisation time (years), steady-state corrosion rate ($\mu m/y$), max. exposure time (years) and type of WS according to ASTM specifications.

Box-whisker plots obtained from statistical processing of the stabilisation times and steady-state corrosion rates for ASTM A-242 WS shown in tables 3 and 4 are presented in figures 3 to 5. The box-whisker type graph represents the statistical data as separate boxes. The box is determined by the 25th and 75th percentiles, and the band inside the box is the median (50th percentile). The ends of the whiskers are determined by the minimum and maximum of all of the data. The small square symbol inside the box is the mean value of the data and x symbols, the 1st and 99th percentiles. These figures reveal the following trends:

(i) The <u>stabilisation time</u> of the rust layer decreases as the corrosivity category of the atmosphere where the WS has been exposed rises (Fig. 3), going from 6-8 years in less aggressive atmospheres to 4-6 years in more corrosive atmospheres.

The stabilisation time of the rust layers depends, among other factors, on the exposure time, the existence of wet/dry cycles, the corrosivity of the atmosphere, and in short on the volume of corrosion products formed. However, a shorter stabilisation time does not imply a greater protective capability of the rust. In this respect, the stabilisation of the rust layer occurs faster in marine atmospheres due to their greater corrosivity, but

the protective value of this rust is lower than that of rusts formed in non-marine atmospheres (rural, urban and light industrial) where the stabilisation times are longer.

(ii)   The steady-state corrosion rate rises in line with the corrosivity of the atmosphere in both rural, urban and industrial atmospheres (Fig. 4) and marine atmospheres (Fig. 5).

A matter of the greatest practical relevance is to know when an unpainted WS can be used. The cost of painting a CS bridge usually represents around 12% of its initial construction cost, with repainting taking place every 6 to 15 years, depending on the aggressivity of the environment to which it is exposed. WS structures normally become more economical than painted CS structures [58] after 15 years in service in environments of moderate aggressivity.

The problem is how to define the environmental conditions of an atmosphere of moderate aggressivity, which is ultimately what determines the applicability of an unpainted WS. From a practical point of view, the criterion followed has been to limit the steady-state corrosion rate of WS in the atmosphere to an acceptable value for material safety, where maintenance operations are not required [59]. Thus, in 1960, after a 15-year atmospheric corrosion test, Larrabee and Coburn [12] suggested that ≤ 5 μm/year was an acceptable corrosion rate for the use of unpainted WS. In Japan unpainted WS can be used for bridge construction in environments where the corrosion loss is ≤ 6 μm/year for the first 50 years of exposure [60], although this criterion has subsequently become more restrictive, and their use is now only advised in environments where the corrosion loss is ≤ 5 μm/year for the first 100 years of exposure [61]. In the USA, Cook [62] reported that the use of unpainted WS was acceptable in places with an average corrosion of up to 120 μm in the first 20 years of exposure, i.e. a corrosion rate of ≤ 6 μm/year.

The fairly widespread criterion of ≤ 5-6 μm/year for long-term atmospheric corrosion suggests only a marginal benefit of using conventional WS in preference to CS in aggressive atmospheres, especially in marine atmospheres [63]. A view of figures 4 and 5, which plot a steady-state corrosion rate of 6 μm/year, indicates that unpainted conventional WS should not be used in atmospheres of corrosivity category $\geq$ C3, marine or otherwise.

(iii)   With regard to the corrosion resistance of the two traditionally most widely used WS, ASTM A-242 and ASTM A-588, view of tables 3 and 4 reveals that ASTM A-588 exhibits poorer corrosion resistance than ASTM A-242 (its steady-state corrosion rates are 50-100% higher than those of ASTM A-242) and a shorter exposure time in the atmosphere before stabilisation of the rust layer.

6.   Effect of exposure conditions

The corrosion characteristics of WS depend in a complex way on climate parameters, pollution levels, exposure conditions (open air, shelter, etc.) and the composition of the steel.

With regard to the effect of exposure conditions on the atmospheric corrosion of WS, only a limited amount of information is available. In this respect it is interesting to cite the work carried out by K. Park in 2004 [64], which makes an exhaustive bibliographic review

considering design aspects such as: angle of exposure depending on the latitude of each site, skyward or groundward orientation, sheltered conditions, continuous moisture conditions, and heavy concentrations of pollutants from rainfall or salt spray, deicing salts, dirt, and debris in industrial and marine environments, etc.

In order for patinas with optimum protective properties to develop, the environmental conditions must act in the appropriate way on the metal surface. In this sense, as has been noted above, it is important that rainwater washes the steel surface well, that accumulated moisture is well-drained, and that drying action is fast. A key condition for the formation of a protective patina is a cyclical variation between wet and dry periods. Periodic flushing followed by drying is desirable. In rain-sheltered areas, the typical dark patina formed on open exposure is not obtained and instead the surface becomes coated with a layer of lighter-coloured rust. Nevertheless, the rust layers are more compact and adherent than on CS and the corrosion rate is usually so low that the absence of dark patina seems to be of only aesthetic significance [32]. An exception is atmospheres with high chloride contents, where the accumulation of hygroscopic chlorides can give rise to very high corrosion rates [65].

6.1   Geometry of exposure

The good performance of WS, low corrosion rate, good surface appearance, and early formation of protective rust films, depend on the geometry of exposure which determines a good washing action of rainwater and easy drainage of moisture. Thus, Matsushima et al. [20] by means of periodic observations of the appearance of rust and corrosion rate measurements showed that good washing of the surface by rainwater was the most important effect for the early development of a protective rust film.

Larrabee [66] and Schikorr [67] noted the importance of the orientation and geometrical configuration of specimens in field exposure tests, i.e. the angle with respect to the horizontal, and differences between the upper and lower sides of the specimens, due primarily to the time of wetness and amount of deposition.

The orientation and angle of exposure significantly affect the corrosion rate. To obtain comparable results, ASTM practice G50 [68] recommends exposing specimens at an orientation and an angle that yield the least amount of corrosion. This condition is met in the northern hemisphere when the sun is above the equator and the specimens face south at an angle equal to the latitude of the test site. Conversely, in the southern hemisphere, specimens should be exposed facing north at an angle equal to the latitude of the test site. Most atmospheric corrosion tests in the United States have been performed at an angle of 30° facing south. However, atmospheric corrosion studies in Europe are usually done with specimens facing south at 45° from the horizontal, owing to the higher latitudes.

6.1.1.   Angle with respect to the horizontal

Several researchers have addressed this issue. In 1951 Laque [69] noted that specimens exposed vertically do not develop protective rusts as those exposed at an angle of 30°, especially in the very severe environment close to the ocean. Laque concluded that vertical exposure has the disadvantage that a few degrees variation from the specified 90° will have a much greater effect on the extent to which the surfaces are shaded than a similar variation from a specified 30° position. In 1966 Larrabee [70] also reported that the angle relative to the

horizontal at which specimens are exposed to the environment affected the corrosion rate of WS.

Coburn et al. [41] presented results obtained after 16 years of exposure of ASTM A-588 Gr.A (originally Cor-Ten B) WS specimens in different atmospheres at two different angles, 30° and 90° (vertical), concluding that exposure at 30° led to lower corrosion rates. These results were consistent with those previously reported by Laque [69] and Larrabee [70]. Meanwhile, Coburn et al. noted that WS specimens exposed facing south showed lower corrosion rates than those facing north due to the fact that direct solar radiation from the south resulted in a shorter time of wetness [41].

Studies carried out by Cosaboom et al. [71] confirm the observations of Coburn et al. [41]. While Cosaboom et al. found that 0° (horizontal) specimens corroded less than 90° (vertical) specimens because they washed and dried within a short time after rainfall, Zoccola et al. [72], in a study carried out in Detroit, noted the reverse to be true, with horizontal specimens corroding more than vertical specimens. Zoccola et al. noted that the test site was subject to the accumulation of road dirt and salts on the steel surfaces, and the horizontal specimens were easily contaminated, promoting prolonged wetness and accelerating steel corrosion rates. Thus, special attention must be paid to horizontal surfaces where hygroscopic deposits, chlorides and sulphates, may accumulate and prolong the time during which the surface is wetted.

The effect of panel orientation was studied also by Knotkova et al [32]. Based on the appearance of the surfaces, the rust found on the specimens facing south, west, and east had an attractive fine texture and dark colour and was comparable in all three orientations. The horizontal specimens were different in appearance: the WS had a light-coloured, coarse-textured but adherent rust layer while the rust on the CS was flaking off locally. Gravimetric measurements revealed that eastward exposure was the most aggressive. Moisture probably dried more slowly on the east-facing specimens and this increased the time during which active corrosion occurred. The largest difference between WS and CS was seen on the south-facing specimens.

6.1.2. Orientation

Larrabee [66] and Zoccola [73] showed that the skyward or groundward orientation of the specimen can affect the atmospheric corrosion rate of WS. The upper surface of steel specimens is generally expected to be wet for a shorter time than the lower surface, which receives no sunshine. In this respect, Oesch and Heimgartner [74] noted that rust on the lower side of a WS exposed to an atmosphere polluted with SO_2 presented a higher concentration of sulphate nests, while the rust formed on the upper side was more compact with fewer flake-offs.

In a study of geometrical factors, Moroishi and Satake [75] assessed the upper and lower sides of CS and WS specimens using specimens with one side painted that were exposed at various angles and directions. The lower side tended to corrode as much as 60-70% more than the upper side, and the extent of corrosion increased as the orientation approached the vertical. These observations correlated with the sulphate concentration in corrosion product layers on specimens that were only exposed on their lower side. On the other hand, specimens whose

upper sides were also exposed behaved differently because of the washout caused by rainfall. These corrosion phenomena were more prominent for carbon steel than for weathering steel.

Knotkova et al. [32] also measured the corrosion rate separately on the upper and lower sides of CS specimens during exposure in a southerly orientation at an exposure angle of 45° from the horizontal. The 7-year results showed a relative retardation of the corrosion process on the lower sides of the specimens, but this conclusion cannot necessarily be applied to all exposures. In cases where large structures are exposed and ventilation conditions are different on downward-facing surfaces, corrosion rates will be substantially different to those noted for standard panels in atmospheric exposure sites.

6.1.3. Other design parameters

Important studies of design parameters and the formation of protective corrosion product layers were conducted by Satake et al. [76] and Matsushima et al. [20] in 1970 and 1974, respectively. These researchers constructed models with the anticipated configurations of WS structures: H-shaped pillars and beams, ceilings, window frames, siding, louvers and stairs. They point out that during the design and maintenance of WS, special attention must be paid to crevice areas that can retain moisture much longer time than open surfaces and in which more aggressive electrolytes may form.

6.2. Environmental conditions

It is of interest to know the effect of climate and pollution variables on the corrosion resistance of WS.

6.2.1. Outdoor exposure

The literature contains abundant references and representations of corrosion versus time for WS exposed in atmospheres of different types: rural, urban, industrial and marine. Figure 6 is an example of this. Such information, however, presents a factor of uncertainty in that the atmospheres are classified in a purely qualitative way according to the location of the testing station and its surroundings, based on a subjective assessment of climate and pollution factors.

According to Knotkova et al. [32], in rural areas the corrosion rate is usually low, and the time needed to develop a protective and nice-looking patina may be quite long. For CS the corrosion rate is also rather low in these conditions (Fig. 7).

In urban environments with SO_2 levels not exceeding about 90 mg SO_2/m^2.d, WS usually show stabilised corrosion rates in the range of 2-6 μm/year, i.e. only slightly higher than in rural atmospheres. CS shows markedly higher corrosion rates in these conditions (Fig. 7).

In more polluted industrial atmospheres with SO_2 levels exceeding 90 mg SO_2/m^2.d, significantly higher corrosion rates are also found for WS (Fig. 7), indicating that the rust layer formed at very high SO_2 pollution is not altogether protective [32]. Although the surface coating may have a dark, pleasant appearance, it cannot be classified as a true patina. In these conditions loose rust particles are also formed. However, the corrosion rate has always been found to be less than that of CS in these environments.

In marine environments polluted with chlorides a protective patina does not develop and the corrosion rate may be high, especially close to the shore. This applies especially to rain-

sheltered surfaces, where the corrosion rate may be very high due to the accumulation of chlorides which are never washed away.

6.2.2. Indoor exposure

In indoor exposure no systematic differences have been observed between WS and CS corrosion rates. The low corrosion rates observed in all cases were due to the low corrosivity of the environment and not the steel composition. Thus, in agreement with Knotkova [32], there is no justification for using WS in indoor conditions.

6.2.3. Shelter exposure

The majority of long-term exposure trials showing the advantages of WS have been carried out in open exposure conditions where the test specimens are freely exposed to the action of rain, wind, and sunshine. However, a large part of all steelwork is sheltered from any direct action of rain and sunshine and it is questionable whether the results from open exposure testing can be applied to sheltered steelwork. Unfortunately, little information is available on corrosion rates in sheltered conditions.

Larrabee [70], Zoccola [73], Cosaboom et al. [71] and Mckenzie [77] conducted tests with both sheltered and open exposure to clarify the effect of sheltering on WS corrosion. Sheltered racks were used for the experiment by Larrabee and Zoccola, whereas Cosaboom et al. conducted experiments by attaching the specimens on an interior girder to achieve a sheltered effect, and on a roof of a building to simulate open exposure. Mckenzie also examined specimens on an interior girder, and exposed a set of specimens not on a roof but in the open, facing prevailing winds.

Larrabee [70] was the first researcher to carry out tests involving partly and completely sheltered test specimens facing north, south, east and west. He found that for a rural site there were only relatively small variations in weight loss that could be attributed to the amount of sheltering and direction of exposure, although sheltered specimens generally had considerably higher corrosion rates than freely exposed specimens. At a marine site he found that fully sheltered specimens corroded more than partly sheltered specimens. This was attributed to the better washing action of rain on the chloride deposits on partly sheltered specimens. However, in later tests at the same site the opposite was found, with fully sheltered specimens corroding less than partly sheltered specimens.

Although the relevance of such information to the particular sheltering of a composite highway bridge is clearly limited, a paper analysing the applicability of results of long-term corrosion tests with WS to the corrosion of highway bridges concluded that steel specimens sheltered from direct rain or sunlight would corrode more than steel fully exposed [78].

In the research carried out by Zoccola [73], vertical specimens were attached on an interior girder of a bridge located on an industrial site and on the roof of a building near the bridge. WS was two times more corroded on sheltered interior girders than in open exposure. It was argued that WS exposed to traffic fumes, road salt and dirt caused the specimens to develop heavy, flaky rust and a significant accumulation of deposits.

Cosaboom et al. [71] mounted specimens vertically and horizontally on interior and exterior girders of a bridge closed to traffic and on the roof of a nearby building on an industrial site.

Both the vertical and horizontal bridge-sheltered specimens lost up to 65% more thickness than those openly exposed on the building roof. Moreover, vertical specimens corroded more on interior girders than on exterior girders while horizontal specimens corroded almost the same on interior and exterior girders.

After 5 years of testing at a rural site McKenzie [77] found little indication of a reduction in the corrosion rate with time in sheltered conditions. In the absence of high chloride levels, corrosion was lower in bridge sheltering than in open exposure. However, in sheltered marine environments the corrosion rates of WS were higher and severe pitting developed.

6.2.4. Continuously moist exposure

In conditions with very long wetness times or permanent wetness, such as exposure in water or soil, the corrosion rate for WS is usually about the same as for CS.

The results of experiments carried out by Larrabee [70] showed that the amount of corrosion loss on WS and CS was high in the wet tunnel where the steels remained continuously moist; especially with water of a low pH, the WS did not perform well in open exposure. The atmosphere in the wet tunnel was so severely corrosive that after one year of exposure the thickness loss of WS was more than 11 times that of the same steel exposed on the roof.

6.2.5. Air-borne pollutants

One of the factors affecting steel corrosion is industrial pollution produced by the burning of fossil fuels. Atmospheric corrosion increases strongly if the air is polluted by smoke gases, particularly sulphur dioxide, or aggressive salts, as in the vicinity of chimneys and marine environments. Atmospheric corrosion is therefore particularly strong in industrial and coastal areas. Corrosion is furthermore much higher if the metal surface is covered by solid particles, such as dust, dirt, and soot, because moisture and salts are then retained for a long time [79].

According to Singh et al. [80], both SO_2 and chlorides change the structure and protective properties of the rust layer.

6.2.5.1 *Sulphur dioxide (SO₂)*

Particular mention should be made of the effect of atmospheric SO_2 pollution on WS corrosion, where the existing literature is rather confusing. While some authors argue that WS are less sensitive to SO_2 than CS, especially for long exposure time, others believe that WS need access to SO_2 or sulphate-containing aerosols to improve their corrosion resistance or report that a low but finite concentration of SO_2 in the atmosphere can actually assist the formation of a protective layer on WS [6].

ISO 9223 [57] notes that "in atmospheres with SO_2 pollution a more protective rust layer is formed". Leygraf and Graedel [6] considers that a certain amount of deposited SO_2 or sulphate aerosols is beneficial for the formation of protective patinas on the surface of WS, but large amounts result in intense acidification of the aqueous layer, triggering dissolution and hindering precipitation.

(a)   Open exposures

Studies into the effect of SO_2 pollution in the atmosphere on WS corrosion are very scarce. Perhaps one of the first studies in which this matter has been directly addressed

is that carried out by Satake and Moroishi [81], who exposed specimens of a low-alloy steel in a network of 12 stations throughout Japan. These authors found a close relationship between first year corrosion losses and the SO_2 concentration in the air, but this relationship was not clearly seen after five years.

Apart from this worthy attempt by Satake and Moroishi, the fact is that few studies have been carried out (supported by an extensive experimentation) to determine the relationship between the atmospheric SO_2 content and WS corrosion.

Knotkova et al. [32] carried out a field study in different atmospheres, cited above, to determine the effect of SO_2 on the atmospheric corrosion of an ASTM A-242 type WS with the denomination "Atmofix" (see Fig. 7), and the following considerations were made:

(i)   In rural and urban atmospheres with low pollution levels, i.e. SO_2 levels of about 40 mg/m^2.day or less, the conditions are suitable for the formation of a highly protective rust layer on low-alloy steels leading eventually to a relatively stable low rate of corrosion. The appearance of the rust layer on WS is characterised by an attractive dark brown to violet colour and a compact structure.

(ii) In more polluted urban and industrial atmospheres, where the annual average pollution level reaches up to 90 mg/m^2.day, the rust layer formed on WS is again dark brown to violet, but its structure is coarser than that observed in rural atmospheres. It is likely that at certain times of the year the higher SO_2 content, coupled with higher humidity, causes local cracking and spalling of the rust layer, requiring the layer to reform in these areas.

(iii) For heavily polluted industrial atmospheres where the SO_2 level is high, the results indicate a higher corrosion rate than is generally seen on WS with a stable rust layer. This indicates that the process of spalling and regrowth of the rust layer is occurring regularly and intensively.

According to Knotkova et al. [32] the corrosion of WS must be a constant function of the SO_2 content, increasing as the SO_2 content rises. For this reason it was desirable to specify a maximum SO_2 level in the atmosphere where WS may be used without protective coatings. Detailed analysis of the data set of long-term test results, supplemented by the results of 3-year tests in the North Bohemian network of stations with more finely graduated SO_2 levels, was very helpful to more precisely define the critical SO_2 level. The results of this analysis indicate a maximum annual average SO_2 content of 90 mg/m^2.day. A summary plot showing this analysis is given in Fig. 8.

It seems that 90 mg SO_2/m^2.day, the limit established by Knotkova et al. [32] may perhaps be excessive. In accordance with the steady-state corrosion rate criterion of 6 µm/year (see chapter 5(ii)), which is widely accepted to consider that unpainted WS may be used, Fig. 9 has been prepared from data obtained in a 8-year study performed at numerous locations within the framework of the UN/ECE International Cooperative Programme on effects on materials, including historic and cultural monuments [26]. Figure 9 shows that the steady-state corrosion rate of $\leq$ 6 µm/year is obtained for atmospheric SO_2 contents of less than 20 mg SO_2/m^2.day. Above this SO_2 level WS

corrosion is accelerated. These results seem to confirm the opinion of Leygraf and Graedel that large amounts of deposited SO_2 result in intense acidification of the aqueous layer existing on WS during the corrosion process triggering dissolution and hindering precipitation [6].

(b)   Sheltered exposures

The results obtained by Knotkova et al. [33] for shed exposures (Stevenson screen) after 5-year tests on WS specimens yielded the following conclusions:

(i)   The rust that forms on WS in shed exposures does not develop the protective quality found in normal exposure to the weather, and

(ii)   The most favourable conditions for WS application came from urban shed exposures. WS corrosion losses at the same localities were lower than those of CS, and locations with good ventilation proved to be especially favourable; e.g. the lower decks of bridges and open galleries. Even though the rust layers in these cases never had the typical appearance of exterior exposures, they were more compact and more adherent on WS than on CS. The difference in steady-state corrosion rates is relatively low, so the final corrosion rates cannot be a motivation for using WS instead of CS.

Table 5 has been prepared using data obtained in a more recent study carried out in the framework of the UN/ECE exposure programme [26], where ASTM A-242 WS specimens were exposed to the open air and inside ventilated boxes (shelters). The steady-state corrosion rate has been calculated, according to the procedure mentioned above in chapter 5, for different testing stations in the two exposure conditions: open air and shelter.

In atmospheres of low corrosivity, where first year CS corrosion remains below 40 μm, the steady-state corrosion rate in sheltered conditions is similar to or less than that corresponding to open air exposure. However, when the first year CS corrosion is higher than 40 μm, the WS corrosion rate in sheltered exposure exceeds that found in open air exposure. In these atmospheres the SO_2 content in the atmosphere is higher, promoting greater steel corrosion in sheltered conditions due to moisture retention and the absence of wash-off by rainwater.

6.2.5.2   *Sea chlorides*

If bibliographic information on the effect of SO_2 on the atmospheric corrosion of WS is scarce, data analysing the effect of atmospheric salinity in marine atmospheres is even scarcer.

The only rigorous study found in the literature was carried out in Japan on 41 bridges through long-term exposure tests (9 years) between 1981 and 1993 by three organisations: the Public Works Research Institute of the Construction Ministry, the Japan Association of Steel Bridge Construction, and the Kozai Club [60]. Figure 10 shows the relationship between atmospheric salinity and WS corrosion, differentiating between two zones according to the adherent or non-adherent nature of the rust formed.

There seems to be a critical air-borne salinity concentration of around 3 mg Cl$^-$/m^2.day (0.05 mg NaCl/dm^2.day) below which the steady-state corrosion rate of conventional WS is less than 6 μm/year, the criterion already mentioned for allowing the use of unpainted WS.

6.2.5.3 *Deicing salts*

Extensive use of deicing salts for snow removal, such as sodium chloride (NaCl) and calcium chloride (CaCl$_2$), began in the early 1960s. The common use of salt has been associated with a significant amount of damage to the environment and highway structures (Murray 1977) [82]. Albrecht and Naeemi [83] list the different ways in which salt contaminates the steel structure.

In the literature it is possible to find results which indicate that specimens at interior and fascia girders were more corroded than roof specimens because of contamination by salt and water from the bridge deck during the winter season [71], and results obtained by Zoccola [73] which show that road spray, dirt and salts were carried by the air blast created by the heavy traffic on the expressway and quickly contaminated horizontal specimens. The prolonged wet period caused by deposits, chlorides and sulphates in close contact with the steel tended to accelerate poultice corrosion.

Other references related with this point include Park [64] and Hein and Sczyslo [84]. The results of the latter study showed that more corrosion occurred in freezing weather, especially on the highway. In the turbid and freezing weather of Merklingen, ASTM A-588 WS corrosion on the highway showed no difference from CS corrosion. In contrast, the corrosion rates for WS and CS attached to the guardrail along the highway in Duisburg, where it was sunny and warm, were comparably lower than in Merklingen.

6.2.6. Other specific microclimates

Results obtained by Knotkova et al. [33] in microclimates of chemical plants, agricultural areas, metallurgical and textile production plants, as well as in automotive and streetcar environments, showed that WS are generally not suited for such applications and their applicability must be established by experimental results in each specific case.

7. Long-term atmospheric corrosion of WS

As the use of WS in civil engineering became more common, it became necessary to estimate in-service corrosion penetration.

The following approaches can be used to predict the corrosion of WS:

a) Direct reference to experimental data in the literature on the behaviour of these steels in rural, urban, industrial and marine environments after different time periods, considering the most similar atmospheres to the site of the planned structure.

b) Taking estimations made for CS and adapting them to WS, applying a reduction coefficient (R) that must logically vary with exposure time and conditions.

c) Based on empirical formulae similar to those developed for CS.

For approach a) it will be necessary to use the broadest possible compilation of corrosion data for WS in a diversity of circumstances. Table 2 presents a compendium of information found in the literature which may be of assistance in this respect. As has been pointed out before, a factor of uncertainty is that atmospheres are generally classified in purely qualitative terms,

based on a subjective assessment of corrosion factors. Moreover, despite the profusion of data on behaviour in the first 10-20 years of exposure, there is a notable lack of information for exposure beyond 20 years.

In this approach could be also of interest to predict atmospheric corrosion resistance of a WS according to its composition, i.e. the presence and proportion of each alloying element in the alloy. This issue is addressed by ASTM standard G101 [85]. For this purpose the standard establishes two corrosion resistance indices based on two sources of historic atmospheric corrosion data for WS, one published by Larrabee and Coburn [12] and the other by Townsend [86]. Basically it consists of fitting the historic corrosion mass loss data to the typical bilogarithmic equation (see Section 7.1.1), and after statistical analysis to obtain an index (for each historic data source) in the form of an equation in which alloying elements are independent variables.

Both indices are dimensionless, on a scale that goes from zero (no resistance to atmospheric corrosion) to 10 (high resistance to atmospheric corrosion).

ASTM standard G101 is currently the only available guide to quantify the atmospheric corrosion resistance of WS as a function of their composition. However, its predictions need to be taken with a degree of caution due to a series of limitations that affect the standard [87]. Thus, for instance, the atmospheric corrosion resistance index obtained from the mass loss data of Larrabee and Coburn [12] cannot be used as a method to predict corrosion for other WS with a different alloying composition. And on the other hand, the atmospheric corrosion resistance index obtained from the historic mass loss data reported by Townsend [86], who used a wider compositional range and a larger number of alloying elements, presents the disadvantage that atmospheric exposure was carried out only in industrial environments, although this does not necessarily prevent the behaviour prediction from being transferable to other types of atmospheres.

With regard to approach b), the information obtained in the worldwide survey (see chapter 4) has been used to prepare Table 6, which shows the relationship (R) between corrosion rates for WS and the corresponding to CS when the rust layer stabilisation time has been reached on these two materials. R is not seen to vary greatly according to the corrosivity of the atmosphere, and remains in the 0.3-0.5 range, indicating a notable reduction in the atmospheric corrosion of steel when using WS.

Finally, with regard to approach c), it is first necessary to examine what laws fit better the behaviour of weathering steels.

7.1   Models governing the evolution of atmospheric corrosion of WS with exposure time (time- dependent models)

7.1.1   Power model

As Bohnenkamp et al. noted in 1974 [35], the corrosion curves of low-alloy steels, like those of mild and carbon steels, are reminiscent of the typical plot of parabolic laws or power functions (Fig. 6).

Thus, most of the experimental atmospheric corrosion data has been found to adhere to the following kinetic relationship:

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

where C is the corrosion after time t, and A and n are constants.

Thus, corrosion penetration data is usually fitted to a power model involving logarithmic transformation of the exposure time and corrosion penetration.

$$\log C = \log A + n \log t \tag{3}$$

This power function (also called the bilogarithmic law) is widely used to predict the atmospheric corrosion behaviour of metallic materials even after long exposure times, and its accuracy and reliability have been demonstrated by a great number of authors: Bohnenkamp et al. [88], Legault and Preban [50], Pourbaix [49], Feliu and Morcillo [89], and Benarie and Lipfert [90], among others.

If the parabolic law is fulfilled, corrosion behaviour will clearly be characterised by only two parameters: corrosion A after the first year of exposure and the time exponent n. When A and n are known for a given steel and exposure site, the predictions may be extended to any length of time. The value of n does not affect first year corrosion but corrosion in successive years, and its contribution becomes increasingly important; even when the first year corrosion (A) is greater in one place than in another, it is perfectly possible for the order of importance of the corrosion process to be reversed after a number of years due to differences in the value of n.

Pourbaix [49] also stated that the bilogarithmic law is valid for different types of atmospheres and for a number of materials and is helpful in extrapolating corrosion results up to 20-30 years from four-year test results.

The value of exponent n can serve as a diagnostic tool to indicate the nature of the relationship: linear ($n = 1$), parabolic ($n = 0.5$), cubic ($n = 0.33$), etc. This is usually explained in terms of deviation from parabolic behaviour as a result of changing diffusion conditions as the film grows [50].

According to Benarie and Lipfert [90], equation (2) is a mass-balance equation showing that the diffusion process is rate-determining, and this rate depends on the diffusive properties of the layer separating the reactants. The exponential law, equation (2), with n close to 0.5, can result from an ideal diffusion-controlled mechanism when all the corrosion products remain on the metal surface. This situation seems to occur in slightly polluted inland atmospheres. On the other hand, n values of more than 0.5 arise due to acceleration of the diffusion process (e.g. as a result of rust detachment by erosion, dissolution, flaking, cracking, etc.). This situation is typical of marine atmospheres, even those with low chloride contents. Conversely, n values of less than 0.5 result from a decrease in the diffusion coefficient with time through recrystallisation, agglomeration, compaction, etc. of the rust layer.

As a rule, $n < 1$. In the special case when $n = 1$, the mean corrosion rate for one-year exposure is equal to A, the intersection of the line on the bilogarithmic plot with the abscissa $t = 1$ year. There is no physical sense in $n > 1$, as $n = 1$ is the limit for unimpeded diffusion (high permeable corrosion products or no layer at all). Values of $n > 1$ occur practically as exceptions, due to outliers in the weight loss determinations.

The lower n is, the more protective the corrosion product layer on the metal surface is. Therefore, n could be used as an indicator for the physico-chemical behaviour of the corrosion

layer and hence for its interactions with the atmospheric environment. The value of n would thus depend both on the metal concerned, the local atmosphere, and the exposure conditions.

On the other hand, the parameter A provides a criterion for gauging short-term atmospheric corrosion susceptibility. It provides a measure of the inherent reactivity of a metal surface as reflected in the tendency for that surface to produce a corrosion product layer in short-term atmospheric exposure [91].

On the basis of Eq. (2), Townsend and Zoccola [42] use as an indicator of the atmospheric corrosion of different WS the time to exhibit a loss of 250 μm calculated by solving Eq. (2) for time:

$$t* = \left(\frac{C*}{A} \right)^{\frac{1}{n}} \tag{4}$$

where $t*$ is the time in years to achieve a 250 μm corrosion loss; $C*$ is the selected corrosion loss (250 μm), and A and n are constants of Eq (2).

Using the information obtained in the literature survey (chapter 4) we have represented using bilogarithmic coordinates the graphs of the evolution of WS corrosion with exposure time, subsequently calculating the exponent n and the correlation coefficient (ρ). Tables 7 and 8 show the results obtained in non-marine and marine atmospheres, respectively. In the vast majority of the stations the data is well adapted to straight lines with high correlation coefficients.

By way of example, Fig. 11 displays on a bilogarithmic scale the evolution of the atmospheric corrosion of ASTM A-242 WS in different types of atmospheres. As can be seen, the points are almost perfectly aligned and the correlation coefficients are fairly close to unity.

The data series do not adapt well to this rule in only a small percentage of cases with regression lines that present lower correlation coefficients (Fig. 12).

Statistical processing of the n slopes as a function of the type of atmosphere (Fig. 13) shows the clear tendency of marine atmospheres to present higher average n values (close to 0.5) than atmospheres without a marine component, where n presents an average value of around 0.3, irrespective of the atmospheric corrosivity category of the exposure site.

Table 9 lists the average values of n for CS and WS in different types of atmospheres. This data may be useful to help to predict long-term atmospheric corrosion of CS and ASTM A-242 WS [92]. No differences are seen within the rural-urban-industrial group in the value of n for each of these types of atmospheres, nor in the atmospheres of a marine nature, whether or not they were close to the shoreline. The latter again confirms the high significance of the marine character of the atmosphere (which does not distinguish between the various chloride levels) in exponent n seen in a prior statistical study [93]. Attention is also drawn to the 65-70% drop in the value of n for WS compared to CS in any atmosphere.

A study of WS by Coburn et al. [41] which considered two different angles of exposure (30° and 90°) and orientations (facing south and facing north) did not show any great effect of either variable on the exponent n value of the Eq. (2). The value of n only acquired slightly higher values on the specimens exposed at a 90° slope and oriented facing north.

With regard to the effect of sheltering on exponent *n* in Eq. (2) for WS, on the basis of 8-year data observed in the UN/ECE exposure programme [26] in a set of 36 testing stations corresponding to 14 countries, Fig. 14 points to an important effect whereby exponent *n* takes on significantly higher values in sheltered exposure than in unsheltered exposure. In a publication by Tidblad et al. [94] based on data obtained in this same UN/ECE programme, the authors note that *n* changes drastically from about 0.5 for shorter exposure times (1-2 years) to less than 0.2 after 8 years of exposure for unsheltered samples, which practically means that the corrosion products are almost completely protective. In sheltered position the exponent *n* changes from about 1.0 to 0.5 during the same period.

7.1.2. Numerical power model

There are examples in the literature [40, 95] of data that does not fully fit Eq. (2). After a certain exposure time in which this function is indeed followed, the results diverge from the predicted behaviour and are fitted by another straight line whose slope is shallower than the first (Fig. 15). The bi-linear graph obtained on log-log coordinates instead obey an equation of the following type:

$$C = C_1 \, t_p^{\,n_1 - n_2} \, t^{\,n_2} \quad (t \geq t_p) \tag{5}$$

where *C* is the corrosion after t years, C_1 is the first year corrosion, t_p is the duration (in years) of the first exposure period whose slope is n_1, and n_2 is the slope of the second period. One possible reason for this singular behaviour may lie in the formation with time of more compact rust layers which impede the diffusion of the reactive species that participate in the corrosion reactions.

McCuen et al. [48] proposed to improve the power model by numerically fitting coefficients *A* and *n* with the non-linear least-squares method directly to the actual values of variables *C* and *t*, not the logarithms of the variables, since the logarithmic transformation lends too much weight to the penetration data for shorter exposure. This eliminates the overall bias, and more accurately predicts penetration for longer exposure times. They refer to this new model as the **numerical power model**, which has the same functional form as the bilogarithmic model.

In order to know what law best predicts the atmospheric corrosion of WS, it is necessary to refer to a greater volume of information that makes reference to exposure times of > 10-20 years. In this respect, McCuen et al. [48] consider that penetration data for exposure times of at least ten years is needed to reliably estimate the penetration at the end of a 50-100 year service life, in contrast to the opinion of Pourbaix [49], who stated that 1 to 4 years exposure data was sufficient to make long-term forecasts (20-30 years).

7.1.3. Power- linear model

McCuen et al. [48] saw that WS corrosion penetration data revealed behaviour differences that could not all be explained by the parabolic model and thus preferred a composite model (power-linear model) consisting of a power function for short exposure times, up to 3 to 5 years, followed by a linear function for longer exposure times. This model is similar to that used to develop standard ISO 9224 [96], which envisages two exposure periods with different corrosion kinetics. In the first period, covering the first ten years of exposure, the growth law is

parabolic (average corrosion rate, r_{av}), while in second period, for times of more than 10 years, the behaviour is linear (steady-state corrosion rate, r_{lin}).

ISO 9224 offers information on guiding corrosion values for CS and WS in each time period according to the atmospheric corrosivity as defined in ISO 9223 [57]. The guiding corrosion values are based on experience obtained with a large number of exposure sites and service performances.

The question of whether this law provides a better prediction of WS corrosion cannot be fully answered until a greater volume of data is available for analysis, with reference to exposure times of at least 20 years. McCuen and Albrecht compared both models (the power model and the power - linear model) using atmospheric corrosion data reported for WS in the United States and concluded that the experimental data fitted the power-linear model better than the power model and thus provided more accurate predictions of long-term atmospheric corrosion [48]. The improvement in accuracy was greatest for plain carbon steel and copper steel data, and less for ASTM A-588 and A-242 steel data.

7.1.4. Bi-linear model

Some refinement of the power-linear model has been reported for Albrecht and Hall [7], where the authors proposed a new bi-linear model based on ISO 9224, called modified ISO 9224 (Fig. 16a), as well as an adjustment of this new bi-linear model that accounts for a modified corrosion rate during the first year of exposure and a steady state during subsequent years. An application of this adjustment for the upper and lower curves in the medium corrosivity category C3 is reported in Figure 16b.

7.2.   Damage (dose-response) functions

Different models have recently been developed with the aim of generalising the corrosion loss over time for different environments, reporting climate and pollutant variables as independent factors. Two of these models are presented below.

Several dose-response functions have been developed within the International Cooperative Programme (ICP) on "Effects on Materials, including Historic and Cultural Monuments" in the framework of the UN/ECE convention on long range transboundary air pollution [97]. These functions have been formulated for WS (Table 10) and are based on both long-term exposures and trend analysis based on repeated one-year measurements, also taking into account unsheltered or sheltered exposure. The degradation of WS over time is expressed by means of mass loss (ML) as a function of climatic parameters (Rh, T) and SO_2 concentration as reported in Table 10. Further details can be found in reference [97].

Finally, Klinesmith et al. [98] mention that all variation related to environmental conditions appears as error variation in the time-dependent models for models that predict corrosion loss as a function of time only. Furthermore, time-dependent models will yield inaccurate predictions when used to estimate corrosion loss in environments that are different from the environment where the model was calibrated. To overcome this problem, a model is proposed that incorporates multiple environmental factors such as time of wetness (TOW), sulphur dioxide (SO_2), chloride content (Cl^-) and temperature (T):

$$C = A t^B \left(\frac{TOW}{D}\right)^E \left(1 + \frac{SO_2}{F}\right)^G \left(1 + \frac{Cl}{H}\right)^I e^{J(T+T_0)} \tag{6}$$

where $A, B, D, E, F, G, H, I, J$ and T_0 are empirical coefficients.

The model was formulated for different metals and the results indicate that it was reliable for use in a broad range of conditions or locations.

According to Landolfo et al. [99], as far as Klinesmith's corrosion model is concerned, the thickness loss values predicted for one year exposure are very close to EN 12500 [100], but in the long-term the model provides an average thickness loss of about 1.7 mm for a design life of 50 years, which is approximately 10-times more than the forecasts given by the other models.

In order to evaluate the differences between several corrosion models and corrosion rates for WS, Landolfo et al. have undertaken a comparison [99]. Good agreement between the selected corrosion models and corrosion rates can be observed in the case of WS for both short- and long -term exposures.

Despite mentioned inconvenients, recent studies on the long-term atmospheric corrosion of WS continue to use the power function ($C = At^n$) because of its simplicity [86, 101], although ignoring the linear part (parabolic-linear model) will introduce considerable error in thickness estimates for long exposure times.

8. Conclusions

The following conclusions can be drawn from the in-depth bibliographic review of information on the atmospheric corrosion data of conventional WS:

a) The rust layer stabilisation (consolidation) time decreases as the corrosivity of the exposure atmosphere rises, dropping from 6-8 years in less corrosive atmospheres (C2-C3) to 4-6 years in more corrosive atmospheres (C3-C5).

b) The steady-state corrosion rate of WS increases with the corrosivity of the atmosphere. The use of unpainted WS (corrosion rate $\leq$ 6 μm/year) is restricted to non-marine atmospheres with low corrosivity, C2-C3 (low).

c) The exposure geometry (angle of exposure, orientation) influences WS corrosion although its impact is only moderate. In contrast, the presence of atmospheric pollutants SO_2 in urban and industrial atmospheres and Cl^- in marine atmospheres have a rather considerable effect on WS corrosion. There seem to be a critical SO_2 level of close to 20 mg SO_2/m^2.d and a critical Cl^- level of around 3 mg/m^2.d above which the application of unpainted conventional WS is not feasible.

d) With regard to the effect of sheltered exposure, in atmospheres of low corrosivity (C2-C3) practically no effect is seen, but when the corrosivity category approaches C4, sheltered exposure accelerates the WS corrosion rate.

e) Continuously moist exposure does not allow the formation of protective rust layers due to the lack of the necessary wet/dry cycles. Furthermore, as in indoor exposure, WS corrosion is not so different to that experienced by CS, and thus the use of WS is not justified.

f) It is very common to use a power function ($C = At^n$), or its logarithmic transformation (*log C = log A + n log t*), to predict the long-term atmospheric corrosion of WS. *n* values for WS, which are in average 33% lower than for CS, are higher in marine atmospheres ($n = 0.5$) than in other types of atmospheres (rural-urban-industrial) ($n = 0.3$).

9. References

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FIGURE CAPTIONS

Figure 1.   Atmospheric corrosion of Cor-Ten B steel and its evolution with exposure time in the industrial atmosphere of Kearny [12]. Comparison with Cu-bearing steel and plain carbon steel (CS).

Figure 2.   Determination of rust layer stabilisation time and steady-state corrosion rate from a plot of exponential decrease function obtained with corrosion rate data at different exposure times.

Figure 3.   Box-whisker plots of rust layer stabilisation time of weathering steel as a function of atmospheric corrosivity category (ISO 9223 [57]).

Figure 4.   Box-whisker plots of weathering steel steady-state corrosion rate as a function of atmospheric corrosivity category (ISO 9223 [57]). Non-marine (rural-urban-industrial) atmospheres.

Figure 5.   Box-whisker plots of weathering steel steady-state corrosion rate as a function of atmospheric corrosivity category (ISO 9223 [57]). Marine atmospheres.

Figure 6.   Typical plots of corrosion versus exposure time for weathering steels (ASTM A-242 (a), due to Schmitt and Gallagher [19], and ASTM A-588 (b), due to Townsend and Zoccola [42] and Shastry, Friel and Townsend [43]) in different types of atmospheres.

Figure 7.   Corrosion versus exposure time for weathering steel (WS) and reference plain carbon steel (CS) in atmospheres with different SO_2 content. Plots have been elaborated from graphs showed in reference [32].

Figure 8.   Corrosion of weathering steel in outdoor atmospheres as a function of SO_2 pollution level [32].

Figure 9.   Variation of atmospheric corrosion rate of conventional weathering steel with atmospheric SO_2 content. Constructed from data corresponding to 8-year exposure, provided by UNECE/PIC Materials [26].

Figure 10.   Influence of airborne salts (atmospheric salinity) on corrosion rate of conventional weathering steel. The figure has been obtained from references [60] and [62].

Figure 11.   Typical log-log plots of weathering steel corrosion versus exposure time at different test sites.

Figure 12.   Log-log plots of weathering steel corrosion versus exposure time in data series not well adapted to the power function ($C = At^n$), with low correlation coefficients (ρ).

Figure 13.   Box-whisker plots of n values in power function ($C = At^n$) for different types of atmospheres.

Figure 14.   Box-whisker plots of n values in power function ($C = At^n$) for sheltered and unsheltered exposures.

Figure 15.   Bi-linear log-log plots of weathering steel corrosion versus exposure time for data series not well adapted to the power function ($C = At^n$) [95].

Figure 16. Bi-linear plots of weathering steel corrosion versus exposure time [7]: (a) Modified ISO 9224 for different ISO 9223 [57] corrosivity categories; (b) Albrecht et al. adjustment and modified ISO 9224 for C3 corrosivity category.
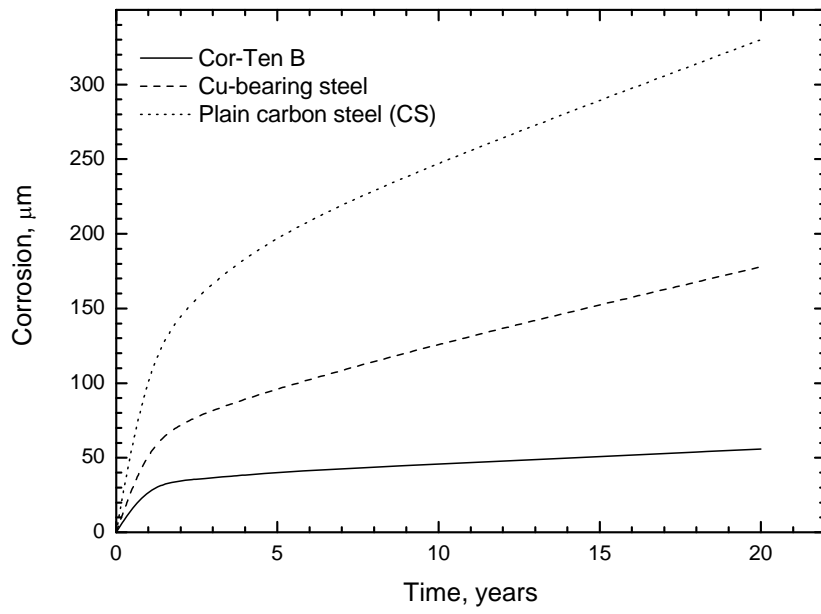
Figure 1.
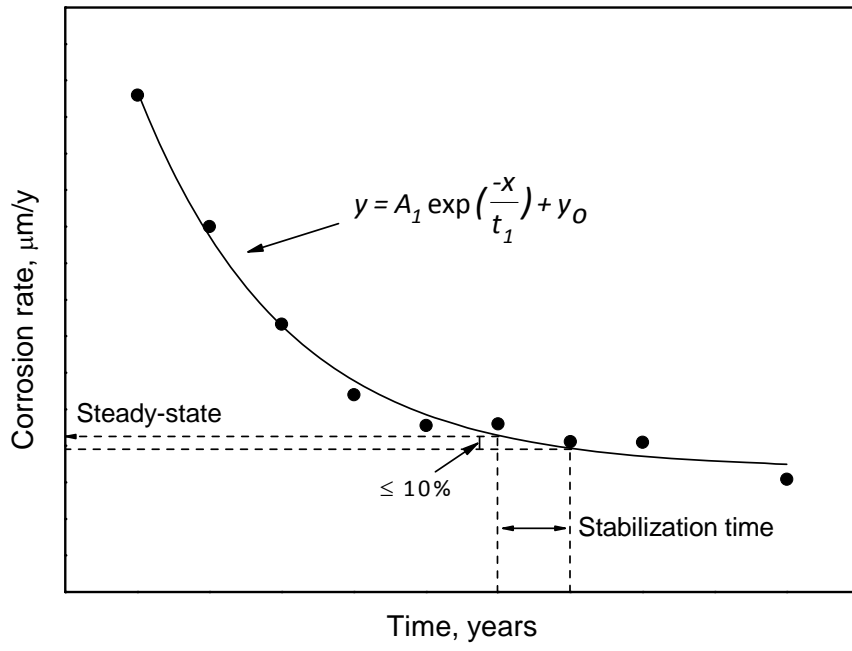
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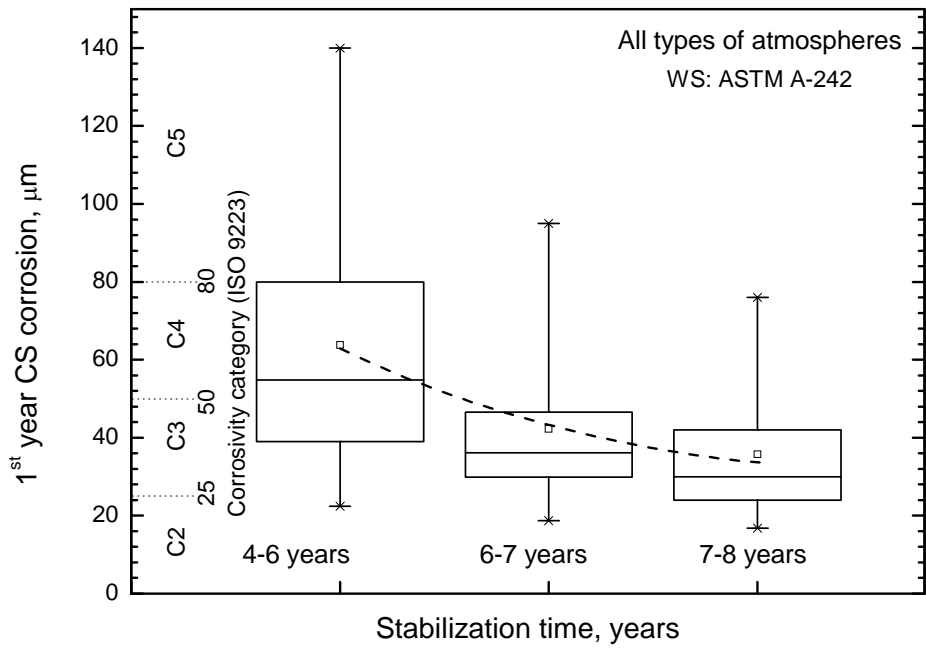
Figure 3

Figure 4

Figure 5

(a)

Corrosion, μm

Time, years

ASTM A-242
(CORTEN A)

— Rural (South Bend)
– – Industrial (Kearny)
····· Marine (Kure Beach, 250)

(b)

Corrosion, μm

Time, years

— Rural (Saylorsburg)
– – Heavily Travelled Expressway (Newark)
····· Industrial (Bethlehem)
–·–·– Marine (Kure Beach, 250)

ASTM A-588
(CORTEN B)
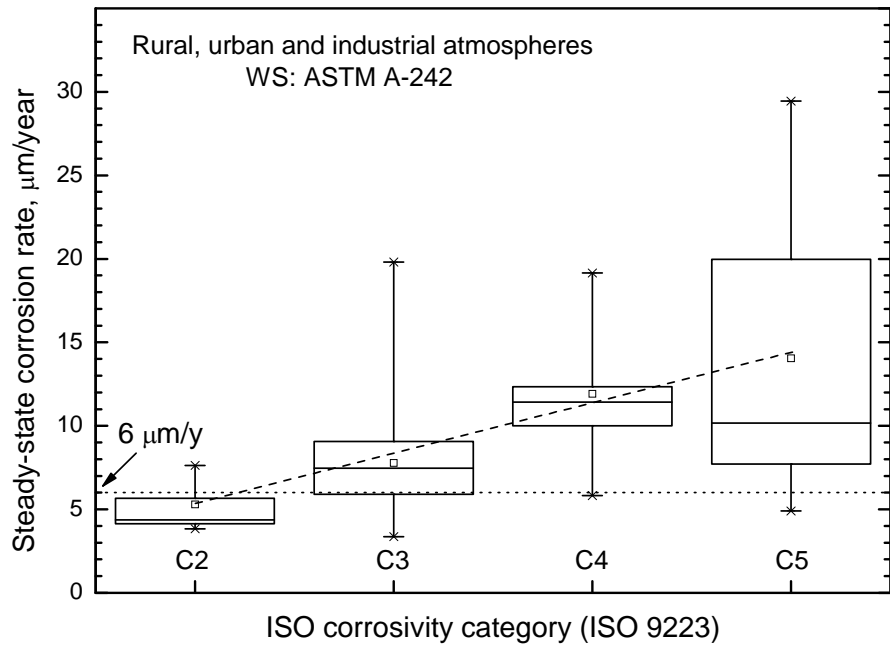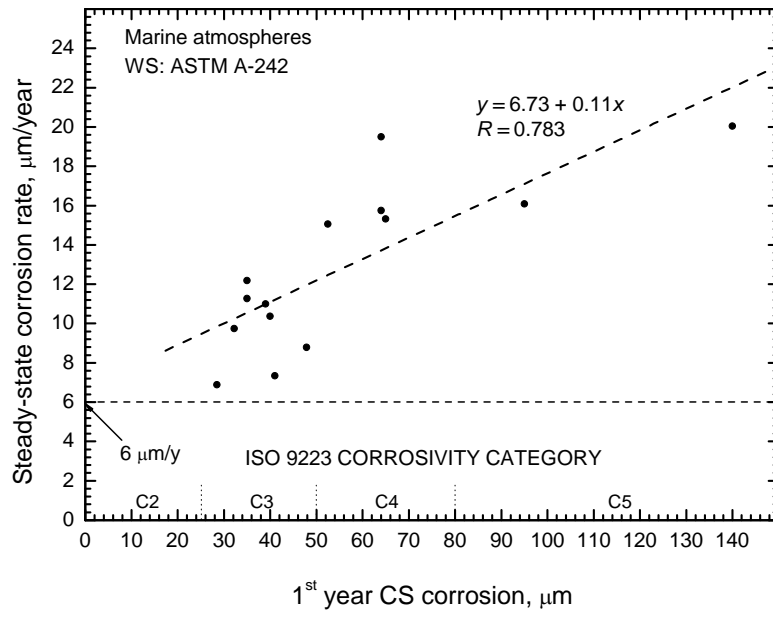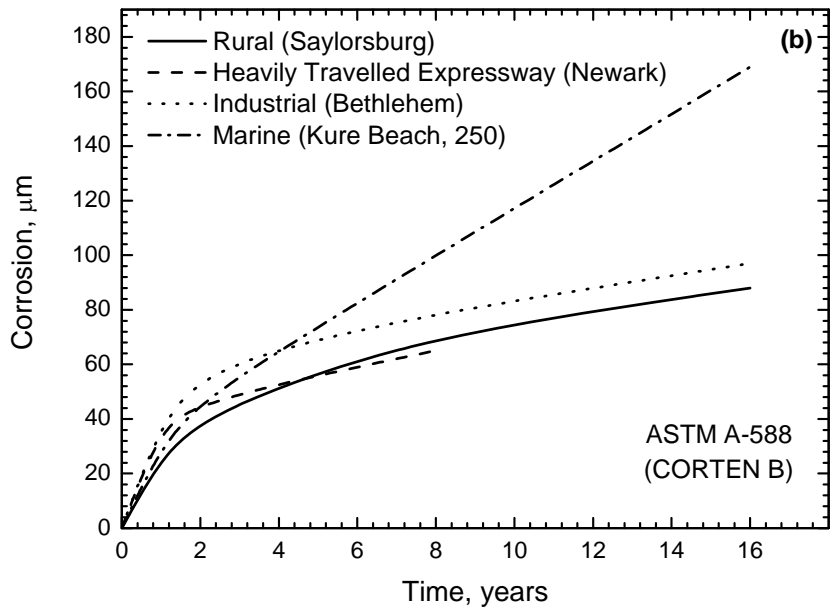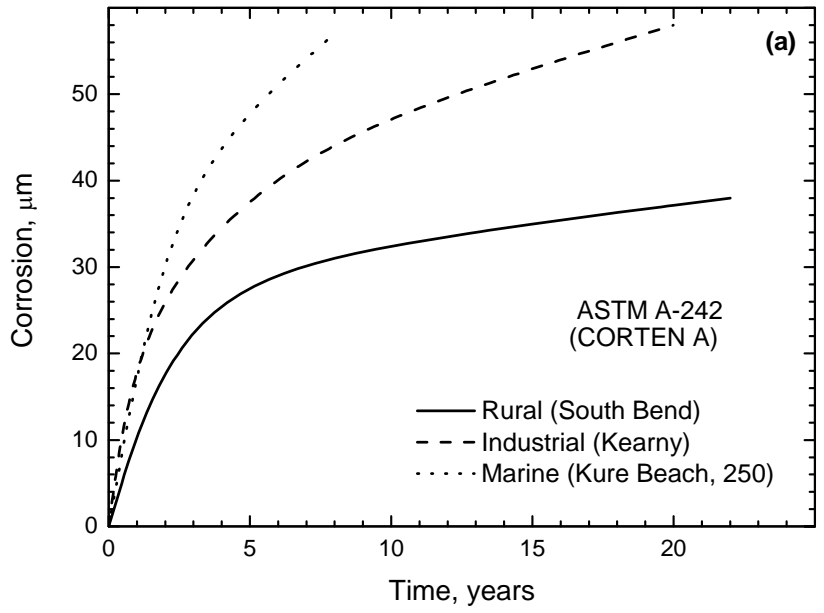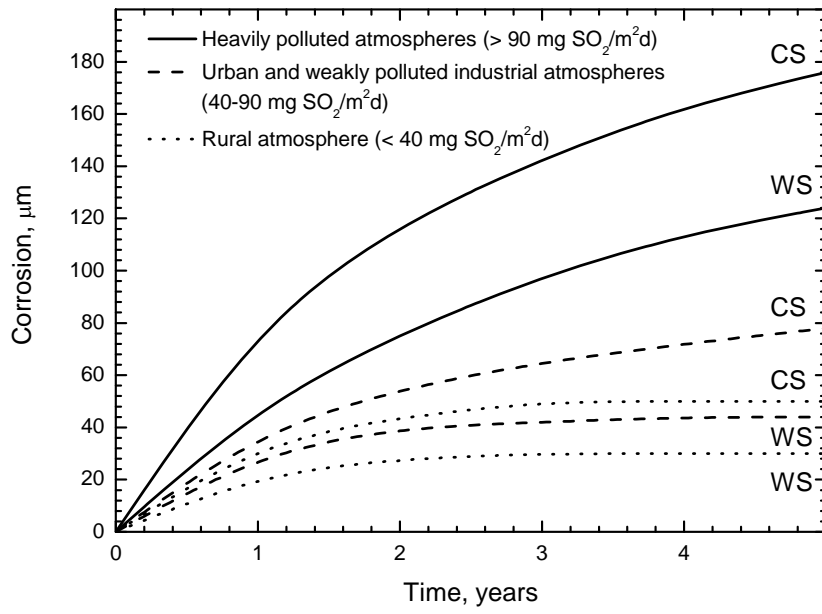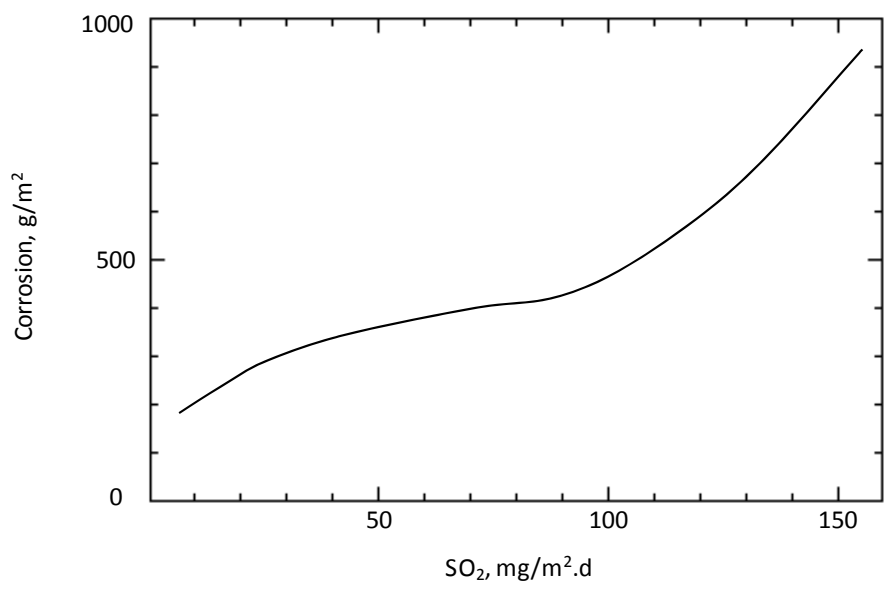
Figure 6

Figure 7

Figure 8
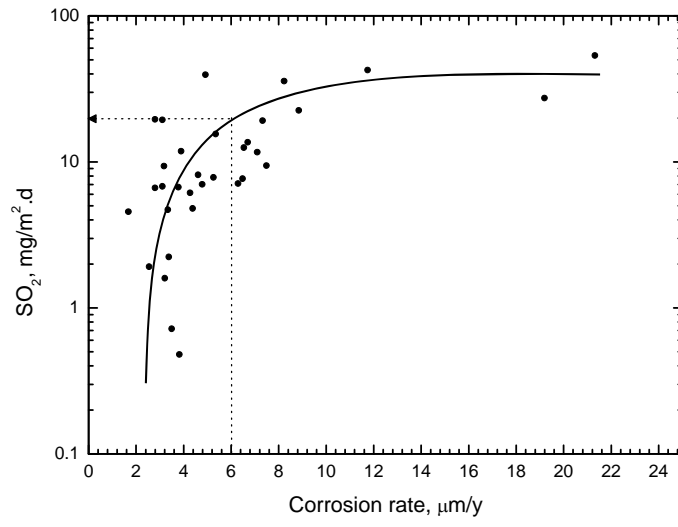
Figure 9
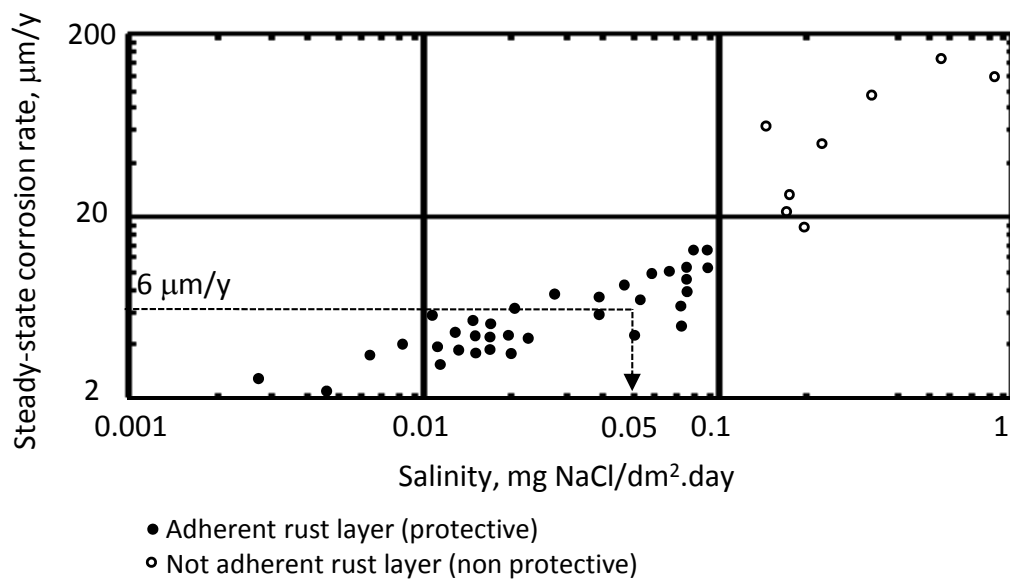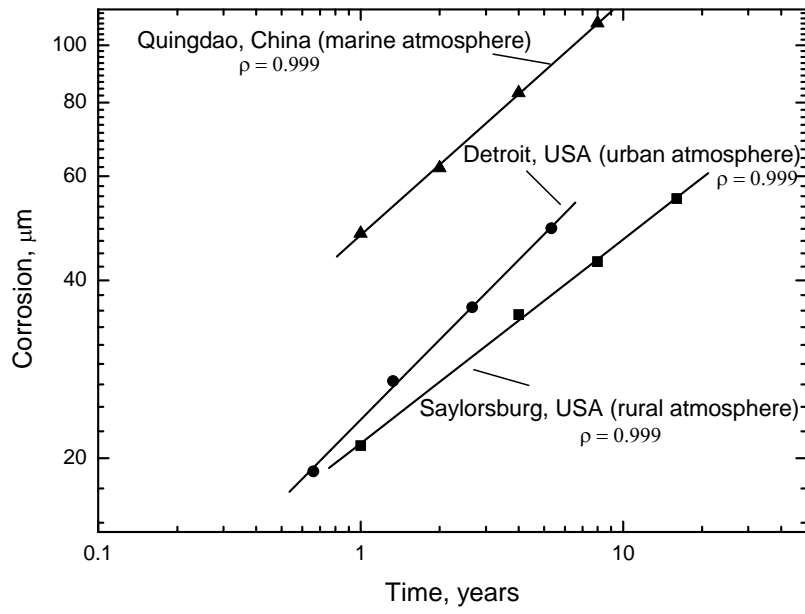
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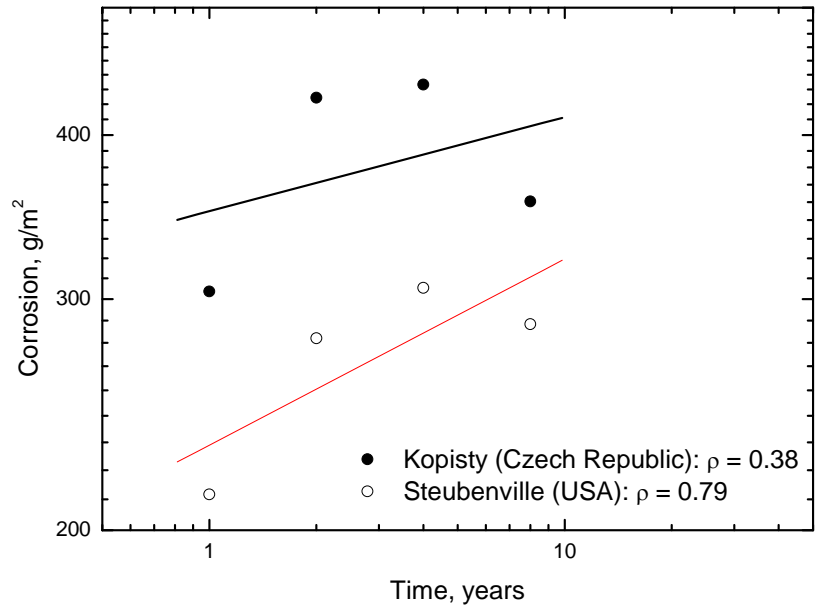
Figure 11

Figure 12

Figure 13

Figure 14

$$C = C_1 \, t_p^{\,n_1 - n_2} \, t^{\,n_2}$$

Slope n_2

log C

log (corrosion)

Slope n_1

log C_1

log t_p

log t

log (time, years)

Figure 15

Modified ISO 9224

(a)

Modified ISO 9224 and Albrecht et al. adjustment for corrosivity category C3

(b)
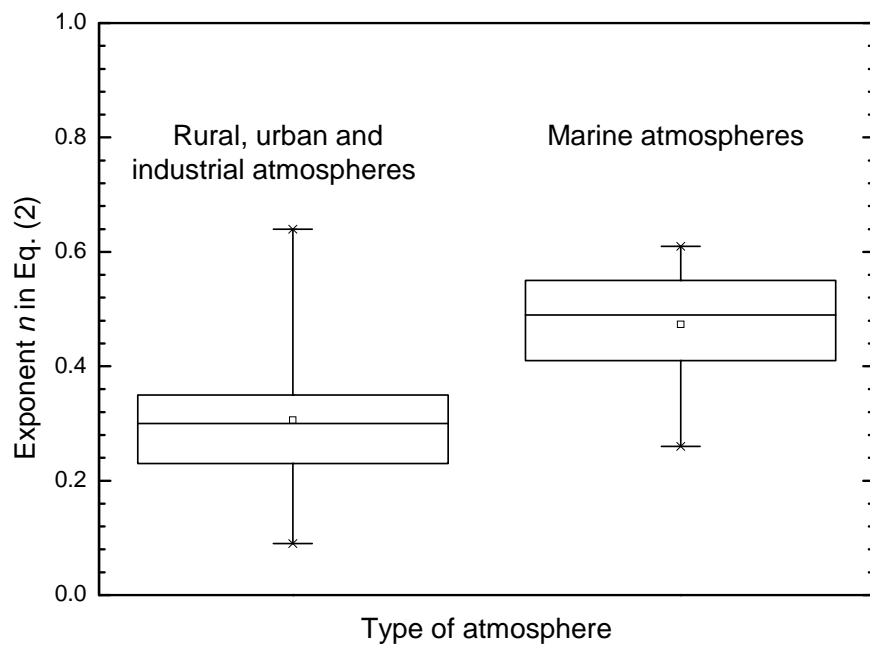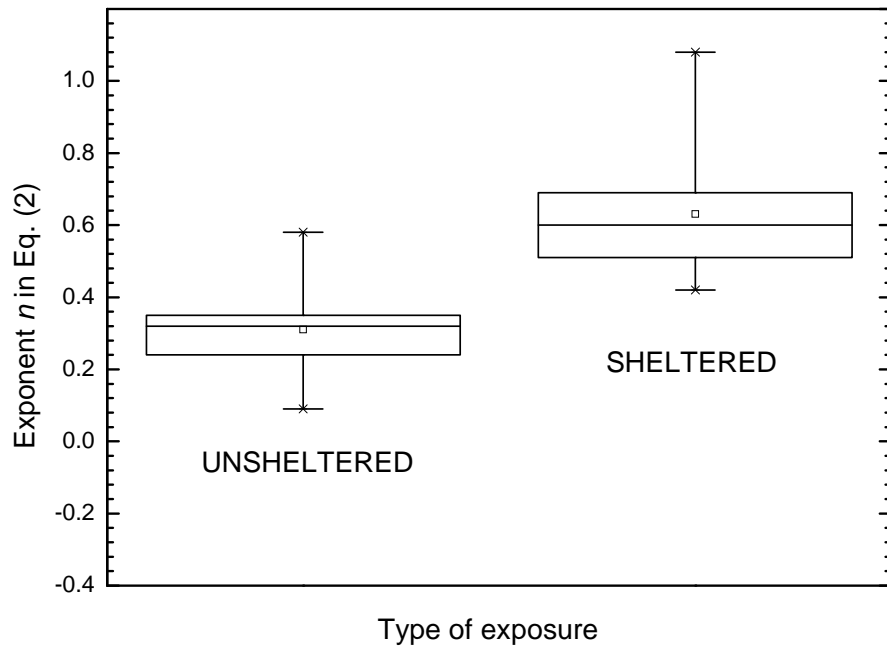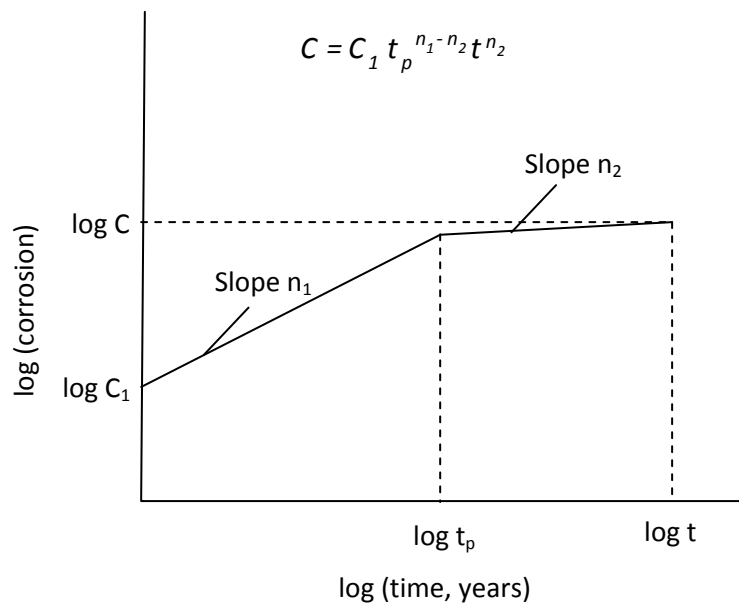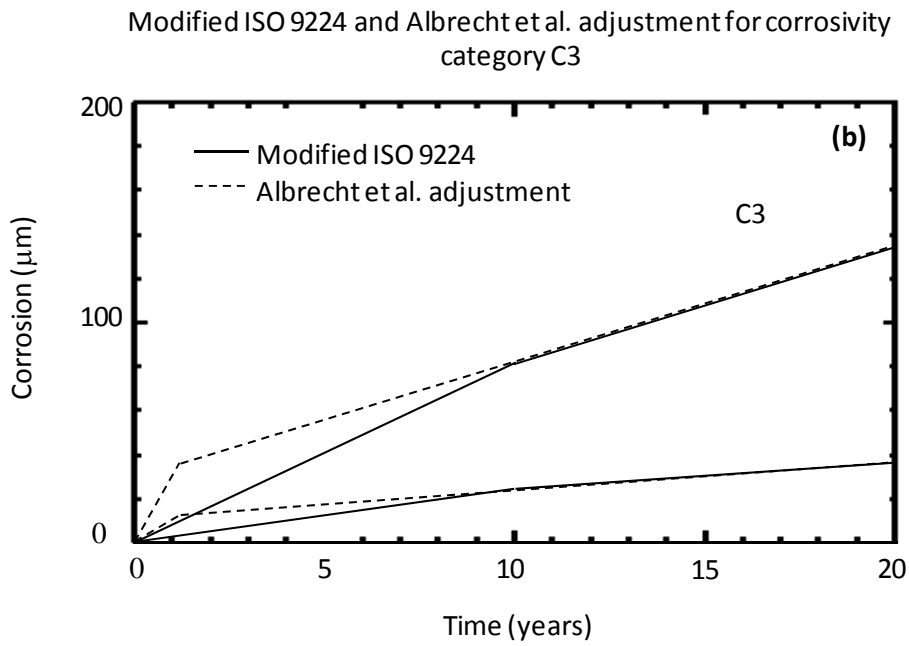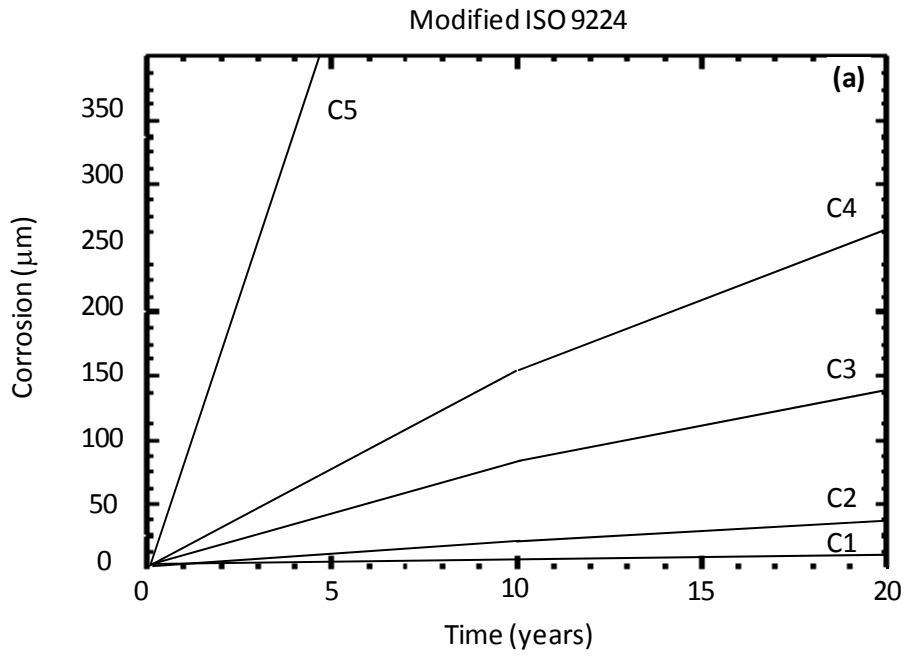
Figure 16

Table 1.   Chemical compositions (weight %) of commonly used WS

Weathering steel	C	Si	Mn	P	S	Cu	Cr	Ni	V
ASTM A-242 (CORTEN A) [2]	≤0.15		≤1.00	≤0.15	< 0.05	≥0.20			
Typical concentrations				≤0.15		0.25-0.40	0.50-0.80	0.50-0.65	
ASTM A-588 Gr.A (CORTEN B) [4]	≤0.19	0.30-0.65	0.80-1.25	≤0.04	<0.05	0.25-0.40	0.40-0.65	≤0.40	0.02-0.10
Typical concentrations				≤0.04		0.30-0.40	0.60-1.00	0.02-0.30	

Table 2. List of atmospheric corrosion exposure tests involving weathering steels carried out in different parts of the world. General characteristics of the tests

R = Rural, I = Industrial, M = Marine

Country	Reference	Test site	Type of atmosphere	Weathering steel (ASTM)	Max. exposure time, years
Belgium	[22-23,49]	Eupen	R*	A-242	4
		Lieja	I*		10
		Ostende I	M*		10
		Ostende II	M*		10
Brazil	[24-25]	Aracaju 1-3	M	A-588	2
		Betim	I		5
		Canoas	I		5
		Cubatao	I		5
		Fortaleza	M		2
		Madre de Deus	M		2
		S. Mateus	R		5
Canada	[26]	Dorset	R*	A-242	8
China	[27-30,51-52]	Beijing	U*	Other	8
		Guangzhou	R*		8
		Jiangjin	I*		8
		Qonghai	R*		8
		Quingdao	M-I*		8
		Wanning	M*		8
		Wuham	U*		8
Czech Rep.	[26,31-33]	Hurbanovo	R-U*	A-242	10
		Karsperske Hory	R*		8
		Kopisty	I*		8
		Prague	U-I*		10
Estonia	[26]	Lahemaa	R*	A-242	8
Finland	[26]	Ahtari	R*	A-242	8
		Espoo	U*		8
		Helsinki	U-I*		8
France	[22-23,49]	Biarritz	M*	A-242	4
		St Germain	R-U*		4
Germany	[22-23,26,34-35,49]	Aschaffenburg	U*	A-242	8
		Bottrop	I*		8
		Cuxhaven	M		8
		Duisburg	I		16
		Düsseldorf	I*		4
		Essen	R*		8
		Gelsenkirchen	I		4
		Langenfeld	R*		8
		Mülheim	I		8
		Olpe	R		8
		Garmisch-Partenkirchen	R*		8
		Waldhof-Laugenbrugge	R*		8
Italy	[22-23,26,49]	Bari	R*	A-242	4
		Lasaccia	R*		8
		Milan	U-I*		8
		Rome	U*		8
		Venice	U*		8
Japan	[36-37]	Amagasaki	I*	Other	5,7
		Kitakyushu	I*		5
Norway	[26]	Birkenes	R*	A-242	8
		Borregaard	I*		8
		Oslo	U*		8

Table 2 (continued)

Country	Ref.	Location	Type	Steel	Value
Netherlands	[22-23,26,49]	Delft	I*	A-242	4
		Den Helder	M*		4
		Eibergen	R*		8
		Vlaardingen	U-I*		8
		Vredepeel	R*		8
		Wijnandsrade	R*		8
Panama	[38]	Limon Bay	M	A-242	16
		Miraflores Lock	R		16
Portugal	[26]	Lisbon	U*	A-242	8
Romania	[54]	Urban-Industrial	U-I	A-242 and	20
		Rural	R	A-588	20
Russia	[26]	Moscow	U-I*	242	8
Spain	[26]	Bilbao	U*	A-242	8
		Madrid	U*		8
		Toledo	R*		8
Sweden	[26]	Aspureten	R*	A-242	8
		Stockholm (Centre)	U*		8
		Stockholm (South)	U*		8
Switzerland	[55]	Bern	U	A-242	8
		Cadenazzo	R		8
		Davos	R		8
		Dubendorf	U		8
		Harkingen	U		8
		Lagern	R		8
		Payerne	R		8
		Sion	R		8
Taiwan	[39-40]	China Steel	I*	Other	6
		Nat. Tsing. Hua Univ	R-U*		5
United Kingdom	[22-23,26,49]	Clateringshowsloch	R	A-242	8
		Lincoln Cathedral	U*		8
		Rye	M*		4
		Stoke Orchard	R*		8
		Stratford	I*		4
		Wells Cathedral	U*		8
USA	[12,19,26,41-50,53]	Bayonne	I	A-242	18.1
		Bethlehem	I	A-242/A-588	16
		Black Island	M	A-242	9.1
		Cincinnati	U	A-242	5.3
		Columbus	U	A-242	10
		Detroit	U	A-242	5.3
		East Chicago	I	A-242	20
		Kearny	I	A-242/A-588	20
		Kure Beach, 25m	M	A-242	7
		Kure Beach, 250m	M	A-242/A-588	16
		Los Angeles	U	A-242	5.3
		Newark	U-I	A-242/A-588	8
		Philadelphia	U	A-242	5.3
		Point Reyes	M	A-242	7
		Potter County	R	A-242/A-588	16
		Rankin	U	A-242	17
		Research Triangle Park	R*	A-242	8
		Saylorsburg	R	A-242/A-588	16
		South Bend	R	A-242	22
		State College	R	A-242	7
		Steubenville	I*	A-242	8
		Washington	U	A-242	5.3
		Whiting	I	A-242	7

*SO_2 concentration data are available

Table 3. Rust layer stabilisation times and steady-state corrosion rates of weathering steels exposed in atmospheres with different corrosivity categories. Non-marine atmospheres (rural, urban and industrial)

ISO corrosivity category [57]	1st year CS corrosion, μm	Test site	Country	Stabilization time, years	Steady-state corrosion rate, μm/y	Max. exposure time, years	WS (ASTM)
	16.8	Ahtari	Finland	7-8	4.4	8	A-242
	18.7	Aspureten	Sweden	6-7	5.7	8	A-242
	19.0	Dorset	Canada	7-8	3.8	8	A-242
	22.4	R. Triangle	USA	5-6	6.9	8	A-242
C2	22.7	Rome	Italy	7-8	4.1	8	A-242
	23.6	Lahemaa	Estonia	6-7	5.6	8	A-242
	24.0	Potter C.	USA	7-8	4.2	16	A-242
	24.0	Potter C.	USA	7-8	8.7	16	A-588
	24.7	Birkenes	Norway	5-6	7.6	8	A-242
	27.1	Aschaffenburg	Germany	7-8	5.9	8	A-242
	27.3	Steubenville	USA	7-8	5.2	8	A-242
	28.3	Madrid	Spain	6-7	4.3	8	A-242
	29.0	Kearny1	USA	6-7	3.9	16	A-242
	29.0	Kearny1	USA	7-8	5.1	16	A-588
	29.2	Oslo	Norway	6-7	6.1	8	A-242
	29.6	Eibergen	Netherlands	6-7	7.1	8	A-242
	29.9	Casaccia	Italy	6-7	6.6	8	A-242
	29.9	Clatteringshaws	UK	5-6	9.7	8	A-242
	30.0	Saylorsburg	USA	7-8	5.4	16	A-242
	30.0	Saylorsburg	USA	6-7	9.7	16	A-588
	30.3	Stockholm S	Sweden	6-7	7.5	8	A-242
	31.2	Venice	Italy	6-7	7.6	8	A-242
	33.0	Wijnandsrade	Netherlands	6-7	7.4	8	A-242
C3	33.5	Stockholm C	Sweden	7-8	7.1	8	A-242
	33.6	Waldhof	Germany	6-7	9.3	8	A-242
	34.5	Espoo	Finland	6-7	8.1	8	A-242
	34.8	Helsinki	Finland	7-8	8.9	8	A-242
	36.1	Vredepeel	Netherlands	6-7	8.8	8	A-242
	37.2	South Bend	USA	10-11	3.4	22	A-242
	37.3	Langenfeld	Germany	6-7	8.9	8	A-242
	39.1	Stoke Orchard	UK	6-7	9.6	8	A-242
	40.1	Lincoln Cath.	UK	4-5	19.8	8	A-242
	42.0	Hurbanovo	Czech R.	7-8	5.9	10	A-242
	43.0	Olpe	Germany	6-7	9.7	8	A-242
	43.6	Essen	Germany	6-7	9.1	8	A-242
	43.8	Vlaardingen	Netherlands	6-7	9.7	8	A-242
	46.6	Milan	Italy	6-7	6.8	8	A-242
	47.5	Bottrop	Germany	7-8	8.2	8	A-242
	50.0	Newark1	USA	5-6	10.3	8	A-588
	51.0	Columbus	USA	6-7	10.7	10	A-242
	54.8	Borregaard	Norway	5-6	13.7	8	A-242
	64.0	Lieja	Bélgica	4-5	19.2	10	A-242
	67.0	Withing	USA	6-7	11.4	7	A-242
C4	69.0	Bethlehem2	USA	6-7	10.0	10	A-242
	71.0	Bayonne	USA	4-5	12.4	18	A-242
	72.0	Rankin	USA	5-6	12.1	10	A-242
	76.0	Bethlehem1	USA	7-8	5.8	16	A-242
	76.0	Bethlehem1	USA	7-8	9.7	16	A-588
	80.0	Newark2	USA	5-6	12.1	7	A-242
	86.0	Prague	Czech R.	6-7	10.2	10	A-242
	88.0	Mülheim	Germany	5-6	20.0	8	A-242
C5	114.0	Duisburg	Germany	5-6	29.5	16	A-242
	116.0	Kearny3	USA	8-9	4.9	20	A-242
	119.0	Kearny2	USA	6-7	5.4	20	A-588
	119.0	Kearny2	USA	4-5	7.7	7.5	A-242

Table 4. Rust layer stabilisation times and steady-state corrosion rates of weathering steels exposed in atmospheres with different corrosivity categories. Marine atmospheres

ISO corrosivity category [57]	1st year CS corrosion, μm	Test site	Country	Stabilization time, years	Steady-state corrosion rate, μm/y	Max. exposure time, years	WS (ASTM)
C3	28.5	Lisbon	Portugal	6-7	6.9	8	A-242
	32.2	Wells Cathedral	UK	5-6	9.8	8	A-242
	35.0	Miraflores Lock	USA	6-7	11.3	16	A-242
	35.0	Miraflores Lock	USA	6-7	12.2	16	A-242
	39.0	Kure Beach2	USA	5-6	11.0	16	A-242
	39.0	Kure Beach2	USA	5-6	14.4	16	A-588
	40.0	Kure Beach1	USA	5-6	10.4	16	A-242
	40.0	Kure Beach1	USA	4-5	17.4	16	A-588
	41.0	Bilbao	Spain	6-7	7.3	8	A-242
	47.9	Kure Beach5	USA	6-7	8.8	8	A-242
C4	52.5	Kure Beach 4	USA	4-5	15.1	16	A-242
	64.0	Limon Bay	USA	6-7	19.5	16	A-242
	64.0	Limon Bay	USA	7-8	15.8	16	A-242
	65.0	Cuxhaven	Germany	5-6	15.3	8	A-242
C5	95.0	Point Reyes	USA	6-7	16.1	7	A-242
	140.0	Kure Beach 3	USA	5-6	20.0	7	A-242

Table 5. Rust layer stabilisation times and steady-state corrosion rates of weathering steels exposed in atmospheres with different corrosivity categories [26]. Unshelter versus shelter exposure

ISO corrosivity category [57]	1st year CS corrosion, μm	Test site	Country	SO₂, μg/m³	Unshelter		Shelter	
					Stabilization time, years	Steady-state corrosion rate, μm/y	Stabilization time, years	Steady-state corrosion rate, μm/y
C2	19.0	Dorset	Canada	2.8	7-8	3.8	7-8	3.7
	22.4	R. Triangle	USA	9.8	5-6	6.9	5-6	6.9
	22.7	Rome	Italy	24.5	7-8	4.1	6-7	3.3
	23.6	Lahemaa	Estonia	0.6	6-7	5.6	7-8	4.4
C3	27.1	Aschaffenburg	Germany	14.8	7-8	5.9	6-7	4.6
	28.3	Madrid	Spain	11.7	6-7	4.3	5-6	4.1
	29.6	Eibergen	Netherlands	7.7	6-7	7.1	4-5	6.2
	29.9	Casaccia	Italy	6.0	6-7	6.6	5-6	5.4
	30.3	Stockholm S	Sweden	8.4	6-7	7.5	7-8	4.2
	31.2	Venice	Italy	15.7	6-7	7.6	3-4	9.0
	33.0	Wijnandsrade	Netherlands	10.2	6-7	7.4	4-5	6.5
	33.5	Stockholm C	Sweden	8.5	7-8	7.1	7-8	4.2
	33.6	Waldhof	Germany	9.6	6-7	9.3	4-5	9.1
	34.5	Espoo	Finland	8.8	6-7	8.1	5-6	6.3
	34.8	Helsinki	Finland	11.8	7-8	8.9	4-5	10.1
	36.1	Vredepeel	Netherlands	8.9	6-7	8.8	4-5	8.3
	37.3	Langenfeld	Germany	19.4	6-7	8.9	6-7	6.6
	39.1	Stoke Orchard	UK	14.6	6-7	9.6	6-7	8.7
	40.1	Lincoln Cath.	UK	17.6	4-5	19.8	2-3	16.2
	43.6	Essen	Germany	24.0	6-7	9.1	3-4	11.4
	43.8	Vlaardingen	Netherlands	28.2	6-7	9.7	2-3	14.8
	47.5	Bottrop	Germany	44.8	7-8	8.2	3-4	10.7
C4	54.8	Borregaard	Norway	34.2	5-6	13.7	3-4	26.8

Table 6.   Relation (R) between weathering steel corrosion rate and plain carbon steel corrosion rate at the rust layer stabilisation time

ISO corrosivity category [57]	1st year CS corrosion, μm	Country	Test site	R (C_{ws}/C_{cs}) at the stabilization time
RURAL, URBAN AND INDUSTRIAL ATMOSPHERES				
C2	24.0	USA	Potter County	0.33
C3	29.0	USA	Kearny 1	0.42
	30.0	USA	Saylorsburg	0.32
	37.0	USA	South Bend	0.28
	42.0	Czech Rep.	Hurbanovo	0.43
	43.0	Germany	Olpe	0.57
			Ave.	0.40
C4	51.0	USA	Columbus	0.49
	64.0	Belgium	Lieja	0.39
	67.0	USA	Withing	0.58
	69.0	USA	Bethlehem 2	0.38
	71.0	USA	Bayonne	0.38
	72.0	USA	Rankin	0.34
	76.0	USA	Bethlehem 1	0.35
			Ave.	0.42
C5	80.0	USA	Newark 2	0.51
	86.0	Czech Rep.	Prague	0.41
	88.0	Germany	Mülheim	0.37
	114.0	Germany	Duisburg	0.47
			Ave.	0.44
MARINE ATMOSPHERES				
C3	35.0	Panama	Miraflores Lock 1	0.52
	35.0	Panama	Miraflores Lock 2	0.56
			Ave.	0.54
C4	53.0	USA	Kure Beach 4	0.41
	64.0	USA	Limon Bay	0.53
	65.0	Germany	Cuxhaven	0.47
			Ave.	0.47
C5	140.0	USA	Kure Beach 3	0.29

C_{ws} = WS (ASTM A-242) corrosion rate
C_{cs} = Plain carbon steel corrosion rate

Table 7. Values of exponent *n* and correlation coefficient in bi-logarithmic plots of the power function ($C = At^n$). Non-marine atmospheres

ISO corrosivity category [57]	1st year CS corrosion, μm	Test site	Country	Exponent *n*	Correlation coefficient
C2	5.7	Toledo	Spain	0.47	0.955
	14.1	Los Angeles	USA	0.35	0.996
	16.8	Ahtari	Finland	0.47	0.969
	16.9	Garmisch	Germany	0.23	0.886
	18.7	Aspureten	Sweden	0.37	0.994
	19.0	Dorset	Canada	0.26	0.916
	21.4	Cincinati	USA	0.27	0.998
	22.4	R. Triangle	USA	0.35	0.995
	22.7	Rome	Italy	0.19	0.938
	23.1	Moscow	Russia	0.25	0.874
	23.6	Lahemaa	Estonia	0.26	0.979
	24.0	Potter County	USA	0.27	0.977
	24.0	Washington	USA	0.33	0.998
	24.7	Birkenes	Norway	0.40	0.996
C3	27.1	Aschaffenburg	Germany	0.33	0.946
	27.3	Steubenville	USA	0.14	0.793
	28.2	Philadelphia	USA	0.29	0.996
	28.3	Madrid	Spain	0.11	0.854
	28.5	Kasperske Hory	Czech R.	0.33	0.866
	29.0	Kearny1	USA	0.22	0.948
	29.2	Oslo	Norway	0.24	0.970
	29.6	Eibergen	Netherlands	0.30	0.959
	29.9	Casaccia	Italy	0.30	0.993
	29.9	Clatteringshaws	UK	0.43	0.993
	30.0	Saylorsburg	USA	0.35	0.999
	30.2	Detroit	USA	0.45	0.999
	30.3	Stockholm S	Sweden	0.24	0.992
	31.2	Venice	Italy	0.34	0.987
	33.0	Wijnandsrade	Netherlands	0.31	0.974
	33.5	Stockholm C	Sweden	0.24	0.940
	33.6	Waldhof	Germany	0.39	0.991
	34.5	Espoo	Finland	0.38	0.992
	34.8	Helsinki	Finland	0.35	0.957
	36.1	Vredepeel	Netherlands	0.35	0.983
	37.3	Langenfeld	Germany	0.32	0.998
	38.0	South Bend	USA	0.16	0.980
	39.1	Stoke Orchard	UK	0.35	0.992
	40.1	Lincoln Cath.	UK	0.58	0.999
	42.0	Hurbanovo	Czech R.	0.14	0.867
	43.0	Olpen	Germany	0.51	0.987
	43.6	Essen	Germany	0.32	0.983
	43.8	Vlaardingen	Netherlands	0.30	0.981
	45.0	State College	USA	0.22	0.919
	46.6	Milan	Italy	0.09	0.888
	47.5	Bottrop	Germany	0.28	0.947
	50.0	Newark1	USA	0.26	0.999

Table 7 (continued)

	51.0	Columbus	USA	0.36	0.965
	54.8	Borregaard	Norway	0.35	0.998
	55.8	Prague	Czech R.	0.22	0.867
	64.0	Lieja	Bélgica	0.64	0.998
	67.0	Whiting	USA	0.17	0.947
C4	69.0	Bethlehem2	USA	0.17	0.950
	70.9	Kopisty	Czech R.	0.07	0.380
	71.0	Bayonne	USA	0.31	0.996
	72.0	Rankin	USA	0.32	0.978
	76.0	Bethlehem1	USA	0.26	0.999
	80.0	Newark2	USA	0.15	0.974
	86.0	Prague	Czech R.	0.18	0.933
	88.0	Mülheim	Germany	0.50	0.998
	100.0	Kopisty	Czech Rep.	0.51	0.999
C5	114.0	Duisburg	Germany	0.61	0.996
	116.0	Kearny3	USA	0.30	1.000
	119.0	Kearny2	USA	0.15	0.973
	210.0	Gelsenkirchen	Germany	0.50	0.998

Table 8. Values of exponent n and correlation coefficient in bi-logarithmic plots of the power function ($C = At^n$). Marine atmospheres

ISO corrosivity category [57]	1st year CS corrosion, μm	Test site	Country	Exponent n	Correlation coefficient
C3	28.5	Lisbon	Portugal	0.31	0.988
	32.2	Wells Cathedral	UK	0.38	0.989
	35.0	Miraflores Lock 1	USA	0.53	1.000
	35.0	Miraflores Lock 2		0.52	0.998
	39.0	Kure Beach2	USA	0.58	0.996
	40.0	Kure Beach1	USA	0.55	0.992
	41.0	Bilbao	Spain	0.26	0.973
	47.9	Kure Beach5	USA	0.45	0.986
C4	52.5	Kure Beach4	USA	0.49	0.998
	64.0	Limon Bay 1	USA	0.51	0.998
	64.0	Limon Bay 2		0.48	1.000
	65.0	Cuxhaven	Germany	0.56	0.996
C5	95.0	Point Reyes	USA	0.46	0.989
	100.0	Ostende 2	Belgium	0.72	0.999
	140.0	Kure Beach3	USA	0.41	0.996
	181.0	Ostende 1	Belgium	1.04	1.000

Table 9. Average values of exponent n in bi-logarithmic plots of the power function ($C = At^n$) for plain carbon steel (CS) and weathering steel (WS) in non-marine (rural-urban-industrial) and marine atmospheres

Steel	Non marine (Rural-Urban-Industrial) atmospheres			Marine atmospheres		
	Number of data	n Ave.	Range of n in Eq. (2)	Number of data	n Ave.	Range of n in Eq. (2)
CS (from ref. [92])	25	0.49	0.26-0.76	13	0.73	0.37-0.98
WS (from tables 7-8)	58	0.33	0.11-0.64	16	0.48	0.26-0.72

Table 10.   Dose-response functions for weathering steel in unsheltered and sheltered exposures [86]

Material	Mass loss, g/m^2
Weathering steel (unsheltered)	$ML = 34[SO_2]^{0.33}\exp\{0.020Rh + f(T)\}t^{0.13}$
Weathering steel (sheltered)	$ML = 8.2[SO_2]^{0.24}\exp\{0.025Rh + f(T)\}t^{0.66}$

where: t = exposure time (years); Rh = relative humidity (%); T = average annual temperature (°C); f(T) = a(T-10) when T < 10°C, otherwise b(T-10), with a, b being constant values depending on the specific metal; SO_2 = sulfur dioxide concentration ($\mu g/m^3$)