Rapid tests of corrosion in corrosion chamber

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Abstract. Concrete is a composite material and it is normally reinforced with steel bars – reinforcement. In reinforced concrete (RC) structures, the concrete is the ideal material for protection of the steel reinforcement, because of its high alkalinity. In the case of steel structures, the protection of members from structural steel is achieved and ensured using coatings or paints. The standard ISO 9223 describes the estimation of corrosion rate \( r_{\text{cor}} \) based on environmental information or measurement of standard specimens during the first year. Based on corrosion rate \( r_{\text{cor}} \), the standard ISO 9224 describes the calculation of overall corrosion loss \( D \) for the following years. Despite these calculations of the corrosion loss \( D \), it is appropriate to perform the measurements on the real samples. However, this process can be time consuming. For this reason, it is useful to use accelerated test in corrosion chamber. Accordingly, the experiment was performed on non-protected carbon steel samples of reinforcement bars and steel plates under 5% sodium chloride solution (\( \text{NaCl} \) environment). The focus of this research was to compare the results of thickness of corrosion loss \( D \) in accelerated corrosion test executed in accordance with the standard ISO 9227 with the calculated values of corrosion loss \( D \) according to the standard ISO 9224.

1. Introduction

The corrosion process is very complicated and extensive issue. Several classifications of the corrosion is given in ISO 8044 [1]. One of the classification is based on the shape of surface corrosion, in general, so-called uniform and local corrosion. This standard also clarifies specific types of corroding surface such as pitting corrosion, crevice corrosion, erosion corrosion, stress corrosion, galvanic corrosion, etc. Another classification is based on the types of conditions in which the corroded metal is placed. Except others, referred are types like underground corrosion, gaseous corrosion, bacterial corrosion or atmospheric corrosion. Last but not least, the classification according to the type of corrosion test, which can be carried out for evaluation of corrosion can be recognized in the standard [1], as well. Actually, several experimental methods are mentioned, like field corrosion test (performed in nature environment), service corrosion test (performed in service conditions), simulated corrosion test (performed under simulated service conditions), accelerated corrosion test (performed under more severe conditions in corrosion chamber), etc.

Consequently, the presented paper is focused on the uniform corrosion under atmospheric condition. This type of corrosion is the most widespread and causes damages not only on the buildings or the cultural heritages but also on the structures of traffic infrastructure. The supporting structures, such as bridges (made of structural steel or reinforced concrete) or non-supporting members, such as bridge rails, parapets, expansion joints and bearings, represent members on road networks that are the most affected by chloride \( \text{Cl}^- \) where deicing salt is applied. In this case, the corrosion rate of chloride measured by the wet candle method [2] can be approximately 90 mg/m²/day in winter seasons [3], which is
considerably higher than in the inland areas with values under 3 mg/m²/day [4], [5]. Therefore, it is necessary to measure the deposition rate of chloride on the traffic infrastructure network as well as to realize in-situ corrosion monitoring on specimens.

2. Models of corrosion
Corrosion rate $r_{\text{corr}}$ (μm/year) expressed as an increase of corrosion depth (corrosion depth-distance between two points, see [1]) per year can vary in different areas not only in Europe [3], [6], [7], [8] but also in the Slovak Republic, as well. The standard ISO 9223 [9] describes two ways how the corrosion rate $r_{\text{corr}}$ may be calculated. The first is based on determination of the corrosion rate $r_{\text{corr}}$ on standard specimens (specimens under outdoor environment). The other is based on environmental information obtained from a net of meteorological measurement points. In Slovakia, the Slovak Hydrometeorological Institute (SHMI) performs such measurements. According to this information, like temperature T, relative humidity Rh, chloride ions $\text{Cl}^-$ and sulphur dioxide $\text{SO}_2$, the corrosion rate $r_{\text{corr}}$ may be calculated by using the dose-response function [9]. The standard [9] also describes so-called categories of corrosivity of the atmosphere (categories from C1 to CX). The category C1 represents very low corrosion rate while the category CX represents the extreme corrosion rate. Furthermore, both a so-called average corrosion rate $r_{\text{av}}$ during the first ten years and steady-state corrosion rate $r_{\text{lin}}$ estimated as an average corrosion rate during the first thirty years are defined in standard ISO 9224 [10], see table 1.

**Table 1.** Corrosion rate for carbon steel for different categories of atmosphere corrosivity [5], [10].

| Category | $r_{\text{corr}}$ (μm/year) | $r_{\text{av}}$ (μm/year) | $r_{\text{lin}}$ (μm/year) |
|----------|-----------------------------|-----------------------------|-----------------------------|
| C1       | $0.0 < r_{\text{corr}} \leq 1.3$ | $0.0 < r_{\text{av}} \leq 0.4$ | $0.0 < r_{\text{lin}} \leq 0.3$ |
| C2       | $1.3 < r_{\text{corr}} \leq 25$ | $0.4 < r_{\text{av}} \leq 8.3$ | $0.3 < r_{\text{lin}} \leq 4.9$ |
| C3       | $25 < r_{\text{corr}} \leq 50$ | $8.3 < r_{\text{av}} \leq 17$ | $4.9 < r_{\text{lin}} \leq 10$ |
| C4       | $50 < r_{\text{corr}} \leq 200$ | $17 < r_{\text{av}} \leq 27$ | $10 < r_{\text{lin}} \leq 16$ |
| C5       | $200 < r_{\text{corr}} \leq 700$ | $27 < r_{\text{av}} \leq 67$ | $16 < r_{\text{lin}} \leq 39$ |
| CX       | $200 < r_{\text{corr}} \leq 700$ | $67 < r_{\text{av}} \leq 233$ | $39 < r_{\text{lin}} \leq 138$ |

Based on the corrosion rate $r_{\text{corr}}$, overall corrosion loss D for following years may be calculated. According to [10], the progress in corrosion loss D during first twenty years is described by power function, equation (1), while the linear function is recommended for the following period, equation (2):

$$D(t \leq 20) = r_{\text{corr}} \cdot t^b$$

$$D(t > 20) = r_{\text{corr}} \left[ 20^b + b(20^{b-1})(t-20) \right]$$

The first fifty years of corrosion loss D according the equations (1), (2) as well as average corrosion rate $r_{\text{av}}$ and steady-state corrosion rate $r_{\text{lin}}$ can be seen in figure 1.

The corrosion model mentioned above is covered by actual standards [9] and [10], but another corrosion models are also available in the literature. Some of them are represented by linear functions, others are described by power function, or the combination of both approaches is utilized. Several corrosion models are given below in equation (3) - (7), the others can be found in references. Corrosion loss D (in units like μm or mm) is usually described by various symbols like D, $\Delta \phi$, $\Delta \phi(t)$, R, $d_{\text{corr}}$, y, etc.
Figure 1. Corrosion loss $D$ calculated according to the equations (1) and (2) and the values of $r_{av}$ and $r_{lin}$.

Klinesmith at al. [11] developed a linear model of corrosion given by the formula:

$$y = A \cdot t^{B} \left( \frac{TOW}{C} \right)^{D} \left( 1 + \frac{[SO_{2}]}{E} \right)^{F} \left( 1 + \frac{[Cl]}{G} \right)^{H} e^{J(t-T_{0})}$$

(3)

Albrecht and Naeemim [12] derived the power function given by following equation:

$$D = y = A_{0} \cdot t^{A}$$

(4)

Andrade [13] modified the model for uniform corrosion loss (the loss of diameter $\phi(t)$) of the reinforcement, which had primary been developed for the marine environment by Bažant [14]:

$$\phi(t) = \phi - 2 \cdot 0.0116 \cdot (t-t_{0}) \cdot i_{corr} = \phi - 0.0232 \cdot (t-t_{0}) \cdot i_{corr}$$

(5)

The loss of diameter $\phi(t)$ can be calculated not only from corrosion current density $i_{corr}$ ($\mu$A/mm$^{2}$) but also from corrosion rate $r_{corr}$ [15]:

$$\phi(t) = \phi - (t-t_{0}) \cdot r_{corr}$$

(6)

Pitting corrosion is described by the following equation:

$$p(t) = 0.0116 \cdot (t-t_{0}) \cdot R \cdot i_{corr}$$

(7)

It should be pointed out that these models were created on the basis of outdoor corrosion tests under various conditions. In the case of non-protected carbon steel (structural steel) the corrosion loss is strongly affected by the surface orientation at the structure (vertical, horizontal or inclined position) [3], [16]. Of course, sheltered or unsheltered placement of steel (if sunlight or rain can affect the samples), pollution and climatological conditions (mainly temperature, relative humidity, chloride, sulphur dioxide), and other effects have influence on the corrosion process, as well. In addition, in the case of reinforced concrete structures, the concrete itself can affect the corrosion process. The process of corrosion in concrete starts in so-called active stage ($t_{0}$, T), e.g. after the passive stage (0, $t_{0}$), during which the reinforced steel is protected by concrete cover. Also the different conditions inside the concrete (before cracking, after cracking or after dropping out the concrete cover) as well as the concrete-reinforcement interaction (by creating pressure at the steel/concrete interface in the phase so-called stress initiation) may affect the corrosion process [17], [18]. Finally, some of the models have been developed for more metals. It means that they can be applied not only for carbon steel but also for zinc, copper, aluminum or weathering steel.
Based on all the above mentioned differences and effects, it is evident that there is a necessity to perform specific corrosion tests in the Slovak Republic under local conditions and to set up individual corrosion test in order to obtain the required information. The following chapters describe the preparation of corrosion tests as well as their partial results.

3. Preparation of corrosion test

As it has already been mentioned, both the steel and the reinforced concrete structures are sensitive to corrosion damages, which have a significant impact on their reliability and durability. Corrosion tests can provide more knowledge about the corrosion process and environmental loads. Consequently, on the basis of this information, better and more suitable protection of the structures against corrosion damage can be then designed. For atmospheric corrosion testing (according to standard ISO 8565 [19]) as well as for the accelerated corrosion testing (according to standard ISO 9227 [20]) were chosen three types of specimens, see figures from 2 to 6. The first samples represent non-protected structures like steel bridges. This samples have dimension of 150x100 mm and thickness of 3 mm. The same shape is also preferred by the ISO 9226 [21] because it is easy to weigh and measure, figures 2, 3 and 5. Second and third type of the samples represent the reinforcement in reinforced concrete structures, either non-protected reinforcement samples (with diameter of ø6 mm, ø10 mm, ø14 mm and ø25 mm and total length 300 mm) or reinforcement covered by concrete in reinforced concrete blocks, figures 3, 4 and 6. Figures 2 - 4 show these three types of samples in atmospheric corrosion test and figures 5 and 6 show them in salt spray environment in corrosion chamber.

![Figure 2. Samples of steel plates in the outdoor environment.](image1)

![Figure 3. Samples of non-protected steel in the outdoor environment.](image2)

![Figure 4. Samples of concrete blocks.](image3)

![Figure 5. Samples of non-protected steel in the corrosion chamber.](image4)

![Figure 6. Samples of concrete blocks in the corrosion chamber.](image5)

As an accelerated corrosion test, a neutral salt spray (NSS) test according to ISO 9227 [20] was chosen. Chloride Cl\textsuperscript{-} environment in this test is dominated, which can represent the environmental load not only on the traffic infrastructure network, where the de-icing salt is applied, but also in the area spanning
hundreds of meters around the roads [22]. It may also be mentioned that this standard describes three types of accelerated test, neutral salt spray (NSS) test, acetic acid salt spray (AASS) test and copper-accelerated acetic acid salt spray (GASS) test. The first one is recommended for metals and alloys. Controlled parameters during the test are concentration of sodium chloride of 50 g/l ± 5 g/l (5%NaCl), temperature 35 °C ± 2 °C and pH of the environment inside the chamber in the range from 6.5 to 7.2.

The duration of the accelerated corrosion test was 1500 hours (62.5 days) for the non-protected reinforcement samples from each diameter and 3360 hours (140 days) for the specimens in the form of steel plates. This time does not include the time when the corrosion chamber was opened for controlling and measuring specimens. Accelerated corrosion test of the concrete reinforcement blocks is more time consuming and it is currently still running. The outdoor corrosion test of concrete reinforced concrete block can take several years or decades. Before starting the test, specimens were labelled, measured and weighed on calibrated scales. Hydrostatic weight (weight under the water) was also measured. On the base of these measurements the bulk density \( \rho \) of each sample was calculated. Mean density of steel plates was 7823.53 kg/m\(^3\) and in the case of reinforcement samples the obtained value was 7822.17 kg/m\(^3\).

4. Results of accelerated corrosion test

Selected intervals for measuring of specimens are shown in table 2. Initial measurements were more frequent (between two and five days) to record the initial corrosion loss curves. For each measurement, two flat sheet samples and two reinforced samples of each diameter (ø6, ø10, ø14, ø25) were taken from the chamber. A total of ten measurements of reinforcement samples and fourteen measurements of steel plates were performed. These samples were visually inspected, photographed, the superficial corrosion products (rust) removed and samples were weighed on calibrated scales. Based on initial measurements of the samples and the weight loss of samples during the test, the corrosion loss \( D_{ch} \) under the salt spray environment according to equations (8), (9) and (10) was calculated. In the case of steel plate samples it can be calculated by equation:

\[
D_{ch,A}(t_{ch,i}) = D_{ch,A}(t_{ch,i-1}) + \frac{\Delta m(t_{ch,i} - t_{ch,i-1})}{\rho S(t_{ch,i-1})} 
\]

In the case of non-protected reinforcement, the corrosion loss \( D_{ch} \) is given by equations:

\[
D_{ch,B}^2 = \phi \cdot D_{ch,B} + \frac{\Delta m}{\pi \cdot l \cdot \rho} = 0
\]

\[
8D_{ch,C}^3 - \left( 8 \cdot \phi + 4 \cdot l_{ch,i} \right) D_{ch,C}^2 + \left( 2 \cdot \phi^2 + 4 \cdot \phi \cdot l_{ch,i} \right) D_{ch,C} - \frac{4 \cdot \Delta m}{\pi \cdot \rho} = 0
\]

The first equation (9) is based on the assumption that the length of sample is constant, i.e. \( l = \) constant (simplified way). The second equation (10) assumes that the length of samples is not constant \( l \neq \) constant, see figures 7 and 8.

![Figure 7. Corrosion loss calculated on the assumption that the length of sample is constant \( l = \) constant, equation (9)](image)

![Figure 8. Corrosion loss calculated on the assumption that the length of sample is not constant \( l \neq \) constant, equation (10)](image)
Table 2. Selected interval for the measurements of specimens

| Measurement number | Steel plate sample number | Reinforcement sample number | Time exploitation in the chamber (hours) | Time between measurements (days) |
|--------------------|---------------------------|----------------------------|-----------------------------------------|---------------------------------|
| 1                  | 1 - 2                     | 1 - 2                      | 0.0                                     | 0.0                             |
| 2                  | 3 - 4                     | 3 - 4                      | 50.4                                    | 2.1                             |
| 3                  | 5 - 6                     | 5 - 6                      | 117.0                                   | 4.9                             |
| 4                  | 7 - 8                     | 7 - 8                      | 217.0                                   | 9.0                             |
| 5                  | 9 - 10                    | 9 - 10                     | 332.4                                   | 13.9                            |
| 6                  | 11 - 12                   | 11 - 12                    | 431.5                                   | 18.0                            |
| 7                  | 13 - 14                   | 13 - 14                    | 649.5                                   | 27.1                            |
| 8                  | 15 - 16                   | 15 - 16                    | 864.1                                   | 36.0                            |
| 9                  | 17 - 18                   | 17 - 18                    | 1080.1                                  | 45.0                            |
| 10                 | 19 - 20                   | 19 - 20                    | 1294.5                                  | 53.9                            |
| 11                 | 21 - 22                   | -                          | 1506.1                                  | 62.8                            |
| 12                 | 23 - 24                   | -                          | 1945.0                                  | 81.0                            |
| 13                 | 25 - 26                   | -                          | 2384.0                                  | 99.3                            |
| 14                 | 27 - 28                   | -                          | 2855.0                                  | 119.0                           |
| 15                 | 29 - 30                   | -                          | 3362.0                                  | 140.1                           |

The following figures show the increasing amount of corrosion product (rust) formatted on the non-protected reinforcement samples, figure 9, and on the plate samples, figure 10.

Figure 9. The accumulation of corrosive products (rust) on the surface of reinforced samples

Figure 10. The accumulation of corrosive products (rust) on the surface of plate samples

5. Discussion and results of accelerated corrosion test

As mentioned above, the main result of the accelerated corrosion test was the serves of corrosion loss $D_{ch}$. The graph in figure 11 shows the corrosion loss $D_{ch}$ of non-protected reinforcement samples and the graph in figure 12 shows the corrosion loss $D_{ch}$ of plate samples.
samples. As can be seen on these graphs as well as in table 3, the corrosion rate curve in the salt spray environment may be described by a linear function. In the case of plate samples, the power function ($R^2 = 99.41\%$) is a little more accurate while the polynomial function is a bit more accurate for the non-protected reinforced samples (the mean value of coefficient of determination for all diameters is $R^2 = 99.39\%$ for the polynomial function, 99.11\% for the linear function and 98.32\% for the power function).

![Figure 10](image)

**Figure 10.** The accumulation of corrosive products (rust) on the surface of plate samples.

![Figure 11](image)

**Figure 11.** Corrosion loss $D_{ch}$ of plate samples

![Figure 12](image)

**Figure 12.** Corrosion loss $D_{ch}$ of non-protected reinforced samples (for diameter ø6 mm)

| Table 3. $R^2$ values for the approximated curves of corrosion loss $D_{corr}$ by polynomial, linear and power function. |
|--------------------------------------------------|
| % Plate samples | ø6 (%) | ø10 (%) | ø14 (%) | ø25 (%) |
|-----------------|--------|--------|--------|--------|
|                 | $D_{ch,A}$ | $D_{ch,B}$ | $D_{ch,C}$ | $D_{ch,B}$ | $D_{ch,C}$ | $D_{ch,B}$ | $D_{ch,C}$ |
| Polynomial function | 99.19  | 99.26  | 99.26  | 99.57  | 99.57  | 98.87  | 98.87  | 99.84  | 99.84  |
| Linear function  | 98.80  | 99.25  | 99.25  | 99.57  | 99.57  | 98.49  | 98.48  | 99.14  | 99.14  |
| Power function   | 99.41  | 99.78  | 99.78  | 99.57  | 99.57  | 94.88  | 94.88  | 99.04  | 99.04  |

The question is, whether it is possible to transfer the results from accelerated corrosion test in practice (outdoor condition). In order to answer this question, it is necessary to answer the questions on two partial issues.

The first issue is related to the tests in the corrosion chamber, where the type of curve (power, linear or combination of both) and the corrosion rate $r_{corr,ch}$ are needed to know.
If the corrosion loss $D_{\text{ch}}$ ($\mu$m) is approximated by the linear function, as seen above, the average corrosion rate $r_{\text{corr, ch}}$ (in unit micrometer per day) can be calculated:

- $r_{\text{corr, ch}} = 3.11 \mu$m/day (plate samples)
- $r_{\text{corr, ch}} = 3.98 \mu$m/day (reinforcement samples for diameter $\phi 6$ mm),
- $r_{\text{corr, ch}} = 3.85 \mu$m/day (reinforcement samples for diameter $\phi 10$ mm),
- $r_{\text{corr, ch}} = 3.93 \mu$m/day (reinforcement samples for diameter $\phi 14$ mm),
- $r_{\text{corr, ch}} = 3.56 \mu$m/day (reinforcement samples for diameter $\phi 25$ mm).

As can be seen, the corrosion rate $r_{\text{corr}}$ of the plate sample is 3.11 $\mu$m/day and the average corrosion rate of reinforcement samples is 3.80 $\mu$m/day. The difference in corrosion rate $r_{\text{corr, ch}}$ can be affected not only by the shape differences (plate samples or reinforcement samples) but also in chemical composition of the steel.

The differences in results as well as the need for testing own samples can also be seen in the standard ISO 9227 [20]. This standard describes the range of corrosion loss to verify the accuracy of the operation of the corrosion chamber and it is in a relatively large extent. The range of corrosion loss corresponding to 48 hours is $70g/m^2 \pm 20 g/m^2$, what is in range from 3.18 $\mu$m/day to 5.76 $\mu$m/day.

The second issue relates to the testing samples under atmospheric conditions (curve of the corrosion loss $D$). For this purpose a calculation according to current standards ISO 9223 [11] and ISO 9224 [10] was chosen, namely the categories of corrosivity of the atmosphere (C2-C3) and corrosion loss according the equation (1) and (2).

The main problem is that the corrosion rate curves $D$ according to this standard are represented by power-linear functions. This is on the contrary to the results of the performed accelerated corrosion tests, according to which (but also other research [23]) the linear function is more accurate. For the comparison there were developed two approaches. The first one is based on the change of time, during which the samples are in the chamber. It means that the daily corrosion rate $r_{\text{corr}}$ during the first twenty years changes every day in order to adapt power function to linear function. The second approach is based on the presumption that several days (one, two, three…) in the corrosion chamber correspond to the course of corrosion loss $D$ in outdoor environment. Both the approaches were applied on the conditions of the Slovak Republic that correspond to the categories of environment corrosivity between C2 and C3 [4], [6].

5.1. The first approach - changing the time during the first twenty years

The graph in the figure 13 represents how many days the samples in the corrosion chamber must be exploited in order to achieve the same corrosion damage as samples in the boundary of C2 and C3 categories of corrosivity. The corrosion rate $r_{\text{corr}}$ for the first year of exposure is $r_{\text{corr}}=1.3 \mu$m/year (the lower limit of category C2), $r_{\text{corr}}=25 \mu$m/year (the upper limit of category C2) and $r_{\text{corr}}=50 \mu$m/year (the upper limit of category C3). The following years were calculated according to ISO 9224 [9], equations (1) and (2). Moreover, it is clear from the figure 13 that the plate sample must be given in the corrosion chamber for longer time to achieve the same damage as reinforcement samples, because their corrosion rate in the chamber $r_{\text{corr, ch}}$ is slightly lower. In the case of plate samples, the considered corrosion rate was $r_{\text{corr, ch}} = 3.11 \mu$m/day while in the case of reinforcement samples, the average corrosion rate for all diameters was $r_{\text{corr, ch}} = 3.80$.

5.2. The second approach – presumption that several days in corrosion chamber correspond to the outdoor environment

In this approach, the presumption that one day exploitation (or three days) in the corrosion chamber environment corresponds to the one year of outdoor environment was observed, figures 14 and 15. In the first case (24 hours in chamber corresponds to one-year outdoor condition) the nearest corrosion loss curve, according the equations (1), (2) is, if the corrosion rate $r_{\text{corr}}$ for the first year is 20 $\mu$m/year. It is near to the boundary between C2 and C3 corrosivity of the atmosphere, figure 14. In the second case (72 hours in chamber correspond to one-year outdoor condition), the nearest corrosion rate $r_{\text{corr}}$ is 48 $\mu$m/year which is very close to the boundary of the corrosivity of the atmosphere C3 and C4, figure 15.
Figure 13. Transformation of the years under outdoor conditions for categories C2 and C3 (horizontal axis) to the days in the corrosion chamber (vertical axis)

Figure 14. Corrosion loss in the corrosion chamber during the 24 hours corresponds to one year of outdoor condition

Figure 15. Corrosion loss in the corrosion chamber during 72 hours corresponds to one year outdoor condition

6. Conclusion
The results of experimental measurements show that the corrosion loss $D_{ch}$ of the reinforcement and plate samples in the corrosion chamber, using a neutral salt spray test according to standard ISO 9227, is very close to linear function. This result was compared to the calculated corrosion rate according the actual standard ISO 9224, in which the first twenty years of corrosion loss $D$ are represented by power function and after that the corrosion loss is described by linear function. Two approaches have been developed to compare the corrosion chamber test results with results calculated according to ISO 9224. In first approach, the first twenty years were represented by different corrosion rate $r_{corr,ch}$ every day, while the second approach assumed the constant corrosion rate per day.

Based on the fact that the results of research of outdoor samples showed different corrosion curves (power, linear function or combination of both), it is needed to provide own measurements under outdoor environment in the Slovak Republic. These measurements must be combined with the cooperation of Slovak Hydrometeorological Institute and also the deposition rate of chloride on the traffic infrastructure network must be measured because the chloride affected the construction where de-icing salt is applied.

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