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Measurement of corrosion rates on reinforcement using the field test

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Abstract

Reinforcement corrosion is a phenomenon that affects not only the durability and serviceability of the structure itself but the economy of the countries, as well. In many cases, structures and bridges must be repaired or reconstructed as a result of corrosion of the reinforcement. In extreme cases, when maintenance is neglected, it is necessary to completely replace the structures with new ones, even if their planned service lifetime has not been reached - it is not enough to strengthen them or it is economically inefficient. Corrosion of the reinforcement primarily causes a reduction in the cross-sectional resistance of the load-bearing elements by reducing the cross-sectional area of the reinforcement, which means a reduction in the force in the reinforcement that it transmits. For this reason, it is necessary to know the rate of corrosion over time depending on the environment in which the element is located. The paper is focused on the experimental measurements of corrosion losses due to atmospheric corrosion on reinforcement samples using the field test. As a part of experimental measurements, corrosion rates on reinforcements of four diameters (diameters 6, 10, 14, and 25 mm) of steel for reinforcement, grade B 500B, are monitored at measuring stations and bridges in various aggressive environments.

Keywords

Corrosion, Reinforcement, Field Test, Specimens, Corrosion Rate, Measurement, Aggressive environment, In-situ Measurements

1 Introduction

There are many factors and/or actions that could decrease the reliability of structures and bridges such, as the movement of a foundation, structural overloading, accidental damage, corrosion, excessive deflections and so on [1,2]. Each type of building or civil engineering works, could be subjected to some of these factors, including climatic conditions. Reliability is the ability of a structure or its member to fulfil the specified requirements during the service lifetime, for which it has been designed. Reliability covers safety, serviceability and durability of a structure [3-6]. Climatic conditions are defined as the long-term prevailing weather conditions and long-term means the period over one year. The corrosion is one of the most general factors which can reduce the designed lifetime (i.e. remaining lifetime) of structures and increase the risk of their failure [7-13]. Climatic parameters and atmospheric pollutions have a high impact on degradation of construction materials like reinforced concrete (RC) or prestressed concrete (PC) structures or bridges [14-15]. This corrosion effect makes any change caused by corrosion like cracking, spalling of concrete cover, decreasing the diameter of reinforced bars, etc. The corrosion effect covers:

- Corrosion attack is the corrosion effect that does not influence the function of structures or its parts/elements.
- Corrosion damage is the corrosion effect that influences the function of structures or its parts elements.
- Corrosion failure is the corrosion effect that characterizes the failure of structures or its parts/elements.

From the point of view of verifying the structures and bridges, it is very important to know the corrosion model and corrosion rate r_{corr}. The paper presents the results of experimental measurements of corrosion rates r_{corr} using the field tests.

2 Measurement of corrosion losses

As can be seen in the following figures, the corrosion effect attacks various types of structures:

- Reinforced concrete (RC) structures such as arch bridge, plate girder bridge, T-beam bridge (Fig. 1),
- Prestressing structures (Fig. 2).
- Abutments or components of the bridge like bearings.

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Figure 1 Corrosion of the RC arch bridge over river in the town Krásno nad Kysucou, Slovakia a), Corrosion of the RC plate girder bridge in the middle of the span, Slovakia b), Corrosion of the RC T-beam footbridge (T cross-section) in the middle of the span in town Prievidza, Slovakia c).

Figure 2 Crack in the middle of span due to corrosion of prestressing steel before the collapse in village Podbiel, Slovakia.

These corrosion effects may lead up to the collapse of the structure. From the point of view of the RC members' evaluation, it is important to know the corrosion model of reinforcement in time and determine the values of the corrosion losses [16]. The corrosion losses r_{corr} can be measured in several ways [17]. It is more accurate and best to measure corrosion losses directly on the existing RC members of structures or bridges (Fig. 1). However, this method is very costly and time-consuming - measurements must take place continuously (preferably annually), it is necessary to select structures for measurement, preferably in various aggressive environments, but with which the owners or administrators of bridges or structures must agree (during the measurement it is necessary to remove the layer of concrete cover, with which the administrator may not agree, or an immediate repair is necessary). The second possible way how to measure the corrosion rates is to measure corrosion losses at measuring stations (field corrosion tests), where only the small samples of reinforcement are stored. This is also financially and time-consuming process lasting even decades, but in this case, it is possible to set up a measuring station (exposure station) in places to take into account different aggressiveness of the environment, as needed (Fig. 3) and there is no need to ask the building owner for permission. The third way is the measurement of corrosion losses in the corrosion chambers - those are the rapid tests in a specific aggressive environment, which can be used to accelerate corrosion and thus shorten the measurement time. In this case, it is possible to determine and verify the impact of individual parameters such as CO_2, SO_2 etc. depending on the type of corrosion chamber.

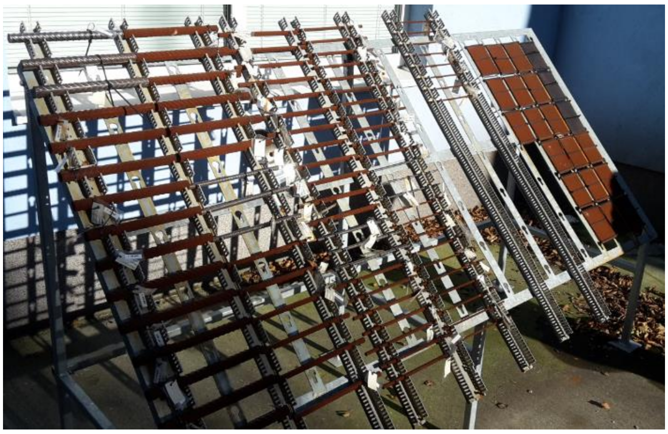

Figure 3 Measurement of corrosion losses - Exposure station (field test) in village Hronský Beňadik.

In this paper, we were focused on measurements of the corrosion rates using the field tests (the second way). In this case it is atmospheric corrosion, not corrosion in concrete, which is not quite the same thing, but it can serve to establish the relationship between them.

3 Results from measurements of corrosion losses using field test

A total of 8 measuring stations were installed. At each station, 4 types of reinforcement diameters were installed - diameters ø6, ø10, ø14 and ø25 mm. The first measuring station was installed in 2017 in village Hronský Beňadik, Slovakia, the next one in 2018. Measurements in 2020-2021 were affected by the situation regarding Covid-19, so the article will present only the measurements from the first installed station in Hronský Beňadik.

The twenty-one samples of each diameter (ø6, ø10, ø14, ø25) were prepared and have been exposed in village Hronský Beňadik, Slovakia on 19/10/2017, see Fig. 3. It was considered that the corrosion losses on three samples (from each diameter) would be measured within one measurement in order to make an average values. The exposure time interval of samples, according to EN ISO 8565 [18], is recommended after 1 year, 2 years, 5 years, 10 years, 15 years or 20 years. So, the similar exposure time intervals (and one more 7th measurement) may be chosen by results obtained from the first few years of measuring. Originally, it was planned to measure in time intervals of 1-2-3-5-10-15-20 years (7 measurements), but due to Covid-19 it was managed to measure after 1 year (16/11/2018), 2 years (17/10/2019) and 4 year (16/11/2021).

During each measurement, three samples of each diameter (ø6, ø10, ø14, ø25) were taken from the rack, inspected, photographed, removed from the corrosion product (rust), weighed and corrosion rate r_{corr} was calculated. In order to verify the effect of cleaning the samples, the first three samples were measured not only after the first year, but at every subsequent measurement, that is, after 2 years and 4 years. The value of the annual corrosion rate r_{corr} [μm/year] or the corrosion rate for a certain period (2 years, 4 years) D_{corr} [μm], were calculated assuming that not only the diameter of the reinforcement, but the length of the sample changes due to corrosion, as well (see Fig 4).

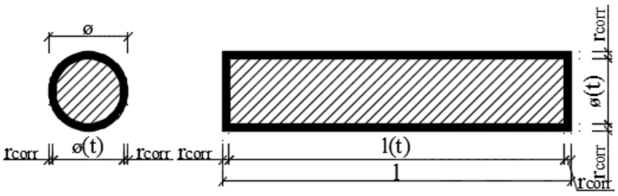

Figure 4 Corrosion rate r_{corr} based on the assumption that the length of the samples is not constant l ≠ constant value.

The length of the sample is changed in time t according to formulas:

$$l(t) = l - 2.r_{corr} \text{ , or} \qquad (1a)$$

$$l(t) = l - 2.D_{corr} \text{ .} \qquad (1b)$$

Diameter of the reinforcement is decreased in time according to formulas:

$$\text{ø}(t) = \text{ø} - 2.r_{corr} \text{ , or} \qquad (2a)$$

$$\text{ø}(t) = \text{ø} - 2.D_{corr} \text{ .} \qquad (2b)$$

The weight loss in time Δm is described by the following formula, where the initial sample weight m_0 at time t = 0 is deducted from the sample weight m(t) at time t ≠ 0:

$$\Delta m = m_0 - m(t) \text{ .} \qquad (3)$$

Similarly, the volume loss in time ΔV can be calculated, i.e. the initial sample weight V_0 minus the sample volume in time V(t):

$$\Delta V = V_0 - V(t) \text{ .} \qquad (4)$$

When the bulk density ρ is a constant parameter, the volume loss in time ΔV is described as:

$$\Delta V\left[m^3\right] = \frac{\Delta m\left[kg\right]}{\rho\left[kg/m^3\right]} \text{ .} \qquad (5)$$

The initial volume V_0 can be calculated using the values initial like cross-section area A_0 and initial length of the sample l:

$$V_0 = A_0.l = \frac{\pi.\text{ø}^2}{4}.l \text{ .} \qquad (6)$$

After substituting the equation (1a,1b) into the equation (4) and (5), one can write:

$$\Delta V = V_0 - V(t) = \frac{\pi.\text{ø}^2}{4}l - \frac{\pi.\text{ø}^2(t)}{4}l(t) = \frac{\pi}{4}\left(\text{ø}^2 l - \text{ø}^2(t)\,l(t)\right) \Rightarrow$$
$$\frac{\Delta m}{\rho} = \frac{\pi}{4}.\left(\text{ø}^2.l - \text{ø}^2(t).l(t)\right) \text{ .} \qquad (7)$$

After simplifying, the cubic equations of the corrosion rate r_{corr} (8a) or corrosion loss D_{corr} (8b) can be created:

$$8.r_{corr}^3 - \left(8.\text{ø} + 4.l\right).r_{corr}^2 + \left(2.\text{ø}^2 + 4.\text{ø}.l\right).r_{corr} - \frac{4.\Delta m}{\pi.\rho} = 0 \text{ , } \qquad (8a)$$

$$8.D_{corr}^3 - \left(8.\text{ø} + 4.l\right).D_{corr}^2 + \left(2.\text{ø}^2 + 4.\text{ø}.l\right).D_{corr} - \frac{4.\Delta m}{\pi.\rho} = 0 \text{ .} \qquad (8b)$$

The measured corrosion rates r_{corr} after the first year, calculated according to formula (8a), are shown in Tables 1-4.

Table 1 Differences between the weight loss and calculation of corrosion rate r_{corr} of the non-protected reinforcement samples after one year of exposure in Hronský Beňadik (station A) for diameter ø6 mm

[no.]	m_0 [g]	$m_{0,w}$ [g]	m(t) [g]	Δm [g]	r_{corr} [μm/year]
1	64.72	56.49	63.98	0.74	15.62
2	65.49	57.14	64.81	0.68	14.01
3	65.17	56.80	64.40	0.77	16.25
			Arithmetic mean:		**15.29**

Table 2 Calculation of the corrosion rate r_{corr} of the non-protected reinforcement samples after one year of exposure for diameter ø10 mm

[no.]	m_0 [g]	$m_{0,w}$ [g]	m(t) [g]	Δm [g]	r_{corr} [μm/year]
1	182.97	159.66	181.94	1.03	12.98
2	181.79	158.61	180.84	0.95	11.94
3	183.49	160.02	182.56	0.93	11.65
			Arithmetic mean:		**12.19**

Table 3 Calculation of the corrosion rate r_{corr} of the non-protected reinforcement samples after one year of exposure for diameter ø14 mm

	m_0	$m_{0,w}$	$m(t)$	Δm	r_{corr}
[no.]	[g]	[g]	[g]	[g]	[μm/year]
1	358.39	312.65	357.06	1.33	11.75
2	358.97	313.18	357.70	1.27	11.18
3	356.89	311.34	355.51	1.38	12.26
			Arithmetic mean:		**11.73**

Table 4 Calculation of the corrosion rate r_{corr} of the non-protected reinforcement samples after one year of exposure for diameter ø25 mm

	m_0	$m_{0,w}$	$m(t)$	Δm	r_{corr}
[no.]	[g]	[g]	[g]	[g]	[μm/year]
1	1152.74	1005.90	1150.79	1.95	6.99
2	1151.53	1004.82	1149.99	1.54	7.42
3	1153.25	1006.28	1151.54	1.71	8.22
			Arithmetic mean:		**7.54**

The arithmetic mean value of the first-year corrosion rate r_{corr} is in the range from r_{corr} = 7.54 μm/year (for diameter ø25 mm) to r_{corr} = 15.29 μm/year (for diameter ø6 mm). The obtained results show that the smaller the diameter of the reinforcement, the greater the corrosion loss r_{corr} and vice versa.

The comparison of corrosion losses D_{corr} over the entire period of four years is also interesting (see Figs. 5-8). The results for the first three samples are actually r_{corr}.

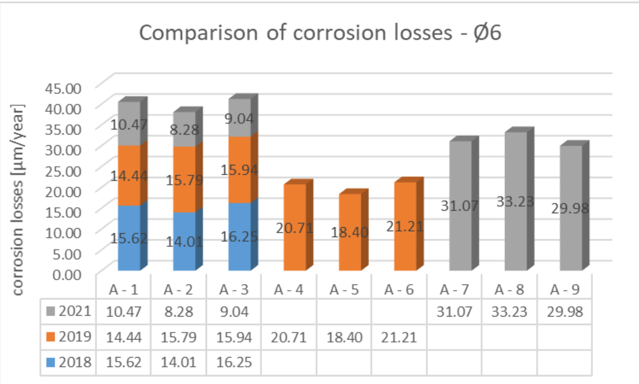

Figure 5 Corrosion losses D_{corr} after four years of measurement for diameter ø6 mm

In all the cases (for all the reinforcement diameters) it was demonstrated that the "effect of cleaning the samples" causes the re-starting (acceleration) of corrosion - corrosion losses on the first samples no. 1-3 are always greater after cleaning than the corrosion losses for the given period (2 or 4 years). This confirms that corrosion products (rust) slow down the corrosion losses, which means that it partially protects the reinforcement.

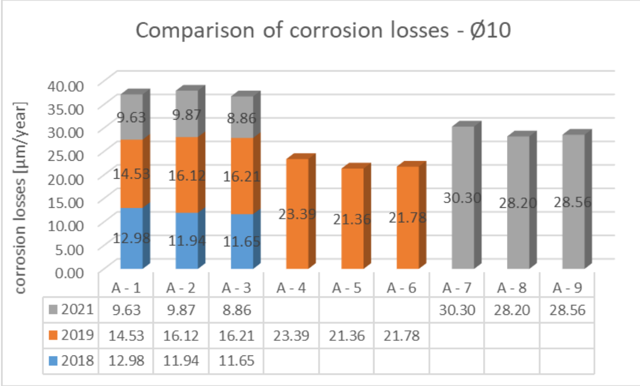

Figure 6 Corrosion losses D_{corr} after four years of measurement for diameter ø10 mm

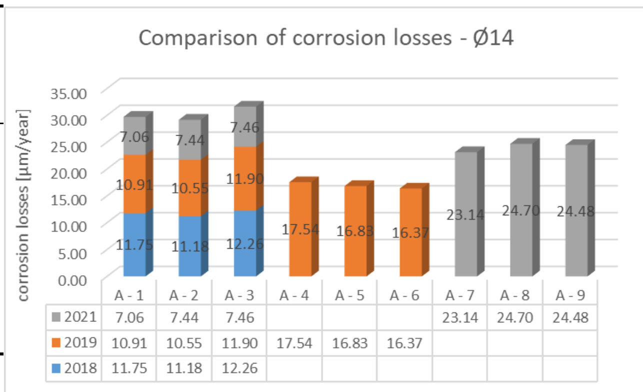

Figure 7 Corrosion losses D_{corr} after four years of measurement for diameter ø14 mm

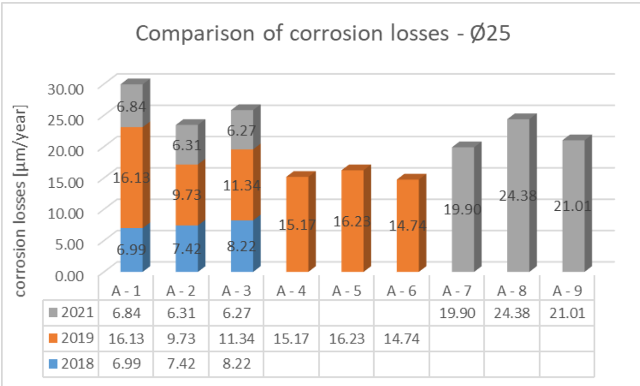

Figure 8 Corrosion losses D_{corr} after four years of measurement for diameter ø25 mm

It should be emphasized that this is atmospheric corrosion in a normal environment, which is not affected by chloride corrosion, as it is in the case of bridges. So, the results are applicable for common reinforced concrete (RC) structures. Even though it is the village of Hronský Beňadik, the measuring station is built in an industrial park - in a zinc factory. So it can be said that it is an industrial environment.

As previously mentioned, the first three samples were cleaned and measured during each measurement. So, it is possible to compare one-year measurements (2017-2018 and 2018-2019) on them, or to compare two-year measurements on samples 1-3 (2019-2021) with samples 4-6 (2017-2019) (see Figs 9-12).

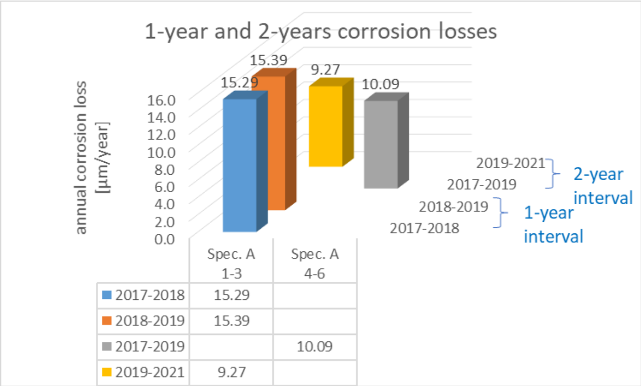

Figure 9 Comparison of the corrosion losses during a one- and two-year interval for diameter ø6 mm

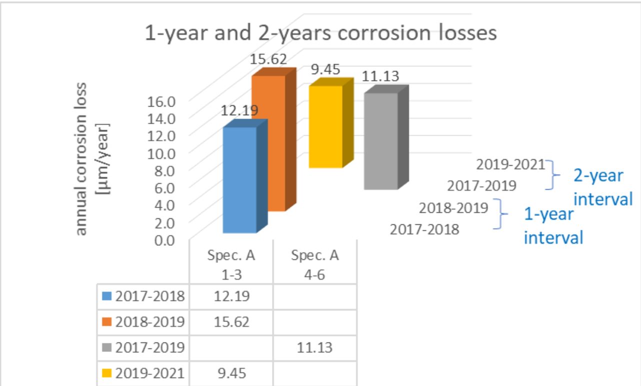

Figure 10 Comparison of the corrosion losses during a one- and two-year interval for diameter ø10 mm

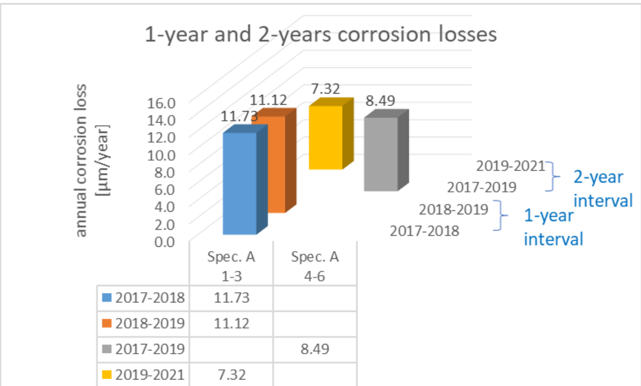

Figure 11 Comparison of the corrosion losses during a one- and two-year interval for diameter ø14 mm

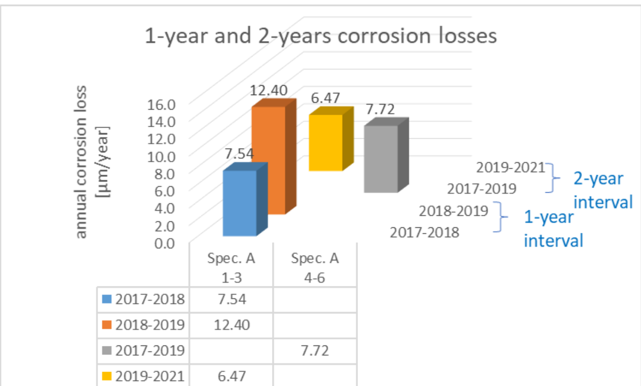

Figure 12 Comparison of the corrosion losses during a one- and two-year interval for diameter ø25 mm

If we compare one-year corrosion losses, larger values were measured for the year 2018-2019 than for the year 2017-2018 (Fig. 9-12). For the year 2018-2019, it no longer applies that the smaller the diameter of the reinforcement, the greater the corrosion loss. This time, the corrosion loss of ø25 (r_{corr} = 12.40 μm/year) was greater than that of the ø14 reinforcement (r_{corr} = 11.12 μm/year), and the largest corrosion loss was measured in the case of ø10 (r_{corr} = 15.62 μm/year).

If we consider a two-year interval (samples 1-3; 2019-2021), the largest corrosion losses D_{corr} were measured at ø14 mm (D_{corr} = 9.45 μm/year), which is only slightly more than at ø6 mm (D_{corr} = 9.27 μm/year). The smallest losses were again measured for ø25 mm (D_{corr} = 6.47 μm/year). Similar, but larger values were also measured within the two-year interval for samples 4-6 for the period 2017-2019. The aggressiveness of the environment in the given area was not measured, therefore it is difficult to evaluate why in the case of samples 1-3 there was an increase in corrosion losses in the period 2018-2019 compared to 2017-2018 and in the case of the two-year interval the values were greater in the interval 2017-2019 (samples 4-6) as in the interval 2019-2021 (samples 1-3). It can only be explained by the fact that in the period 2018-2019, the aggressiveness of the environment was probably the greatest, which caused the greatest increase in corrosion losses on all samples.

4 Conclusions

New structures and bridges are designed for the service life (T_d = 50 years for buildings, T_d = 100 years for bridges). They must withstand all the loads during their lifetime. This means not only the effect of vertical and horizontal loads, but the aggressiveness of the environment, as well. However, we also have many existing structures and bridges that we need to evaluate [19-21]. From the point of view of evaluating the existing structure, it is very important to know the corrosion losses (r_{corr}) and the corrosion model. These are the input parameters that influence the change in resistance of the RC members at time t (e.g. bending resistance, shear resistance etc.). Based on these data, it is possible to determine not only the current state (resistance) of the RC elements, but the change in resistance at time t, as well. From this it is possible to determine the residual (remaining) lifetime of a structure.

The paper presents measurements of corrosion loss values on samples located at measuring stations (field tests). Thus, far, measurements are presented at only one station in the village of Hronský Beňadik, where these measurements have been taking place for the fourth year (2017 sampling, measurement in 2018, 2019 and 2021). Measurements are performed on reinforcements of a diameter of 6, 10, 14 and 25 mm. Within one measurement (one series), 3 samples were always measured and the arithmetic mean of the values was calculated from them.

The results of the measurements show that the larger the diameter of the reinforcement, the smaller the corrosion loss. It is probably caused by the production of the reinforcement - the reinforcements can have different surface properties from production. The aggressiveness of the environment also affects the size of corrosion losses. From the measured values, it seems that the greatest aggressiveness causing the greatest corrosion losses was around 2019 (period 16/11/2018 - 17/10/2019). In addition, the adverse effect of sample cleaning was proven, which accelerates corrosion again - the biggest corrosion losses are after the first year, then the corrosion products partially slow down the further corrosion. Corrosion loss measurements continue at other measuring stations, which started one year later. Therefore, these results will be presented in the future. In the future research objectives, the aspects of climate change e.g. the analysis of the deterioration processes detectable with the Ahrenius equations will also be explored more deeply. Here in relation to the corrosion and carbonation processes, which are often shown to be the triggers of corrosion, using as drivers a temperature increase and a CO2 increase from studies of 380 to 1100 ppm from studies up to 2080. One can observe an acceleration of up to 50 % in these studies with an average temperature increase from 20 to 25°.

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