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**Stray current corrosion of steel in concrete: An assessment of the influencing factors and their consequences on protection criteria**

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**Streustromkorrosion von Stahl in Beton: Eine Bewertung der Einflussfaktoren und deren Auswirkungen auf die Schutzkriterien**

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## **Abstract**

Stray current corrosion of steel in concrete: An assessment of the influencing factors and their consequences on protection criteria

The known model approach for AC corrosion is basically frequency independent in the range of 0.01 to 50 Hz and was investigated in detail at low frequencies. It was found that large amounts of anodic charge can be converted without corrosion by means of re- and discharging the rust layer. This was already empirically proven by Bette in 2005 and has in the meanwhile been confirmed in further investigations.

These observations are of central importance in the assessment of the risk of facilities such as cathodically protected structures and structures embedded in concrete that are subject to stray current influence. For example, an 80-year-old railway infrastructure with average anodic influences of significantly more than 1 V has so far shown no damage, although according to the present standards there is an immediate need for action.

A further normative contradiction exists in the case of cathodically protected pipelines, which are subject to more stringent criteria regarding anodic influences than non-cathodically protected pipelines. This problem has been solved pragmatically in ISO 21857 and is in good agreement with the present model approach. However, it contradicts EN 50162.

As the revision of EN 50162 is currently under discussion, various tests have been carried out to demonstrate the problem of corrosion of steel in concrete under the influence of stray currents.

## **Zusammenfassung**

Streustromkorrosion von Stahl in Beton: Eine Bewertung der Einflussfaktoren und deren Auswirkungen auf die Schutzkriterien

Der bekannte Modellansatz für Wechselstromkorrosion ist grundsätzlich im Bereich von 0.01 bis 50 Hz frequenzunabhängig und wurde bei tiefen Frequenzen im Detail untersucht. Es wurde gefunden, dass grosse anodische Ladungsmengen ohne Korrosion über die Umladung in der Rostschicht umgesetzt werden können. Dies wurde bereits von Bette 2005 empirisch nachgewiesen und seither in weiteren Untersuchungen bestätigt.

Diese Beobachtungen sind von zentraler Bedeutung bei der Bewertung der Gefährdung von Anlagen, wie kathodisch geschützte und einbetonierte Strukturen, welche einer Streustrombeeinflussung unterliegen. So zeigt eine 80-jährigen Bahn Infrastruktur bei mittleren anodischen Beeinflussungen von deutlich mehr als 1 V bisher keine Schäden obwohl gemäss der aktuellen Normenvorgaben unmittelbarer Handlungsbedarf besteht.

Ein weiterer normativer Widerspruch besteht für den Fall von kathodisch geschützten Rohrleitungen, welche den strengeren Kriterien in Bezug auf anodische Beeinflussungen unterliegen als nicht kathodisch geschützte Rohrleitungen. Diese Problematik ist in der ISO 21857 in pragmatischer Weise gelöst worden und ist in guter Übereinstimmung mit dem Modellansatz. Sie steht jedoch im Widerspruch zur EN 50162.

Da aktuell die Revision der EN 50162 diskutiert wird, wurden verschiedene Versuche durchgeführt, welche die Problematik der Korrosion von Stahl in Beton unter Streustrombeeinflussung zeigen sollten.

## 1. Situation

The model approach for AC corrosion shown in Figure 1 is basically frequency independent in the range of 0.01 to 50 Hz. The underlying processes were investigated in detail primarily at low frequencies [1, 2]. This led to the conclusion that with any type of temporally variant influence with anodic and cathodic half-waves, large anodic charge can be consumed without corrosion by re- and discharging of the rust layer [3]. A prerequisite for this is that the amount of charge is sufficiently cathodic on average over time. This effect has already been empirically proven by Bette 2005 [4]. More recent investigations within the framework of a GERG research project have confirmed the correctness of these considerations [5]. The latest results from Italy also conclude that anodic currents do not necessarily have to be associated with corrosion [6].

These observations are of central importance when assessing the stray current influence of facilities. This applies in particular to cathodically protected structures embedded in soil. In these cases, it can be assumed on the basis of the available results that the hazard due to the effects described above is significantly lower than previously assumed. In fact, this assumption coincides with the observation of operators. The railway infrastructure in the canton of Ticino in Switzerland, for example, shows average anodic influences of significantly more than 1 V in some sections due to the connection with the Italian railway network. Considering the allowable maximum influence of 0.2 V according to EN 50162, a direct risk of corrosion of the prestressed reinforced concrete bridges is to be expected on these sections of the railway. However, a further examination of the situation in Chiasso has shown that, despite the strong influence, no damage has yet occurred to catenary masts that are already 80 years in operation. Due to the present standard specifications, however, there would be immediate need for action.

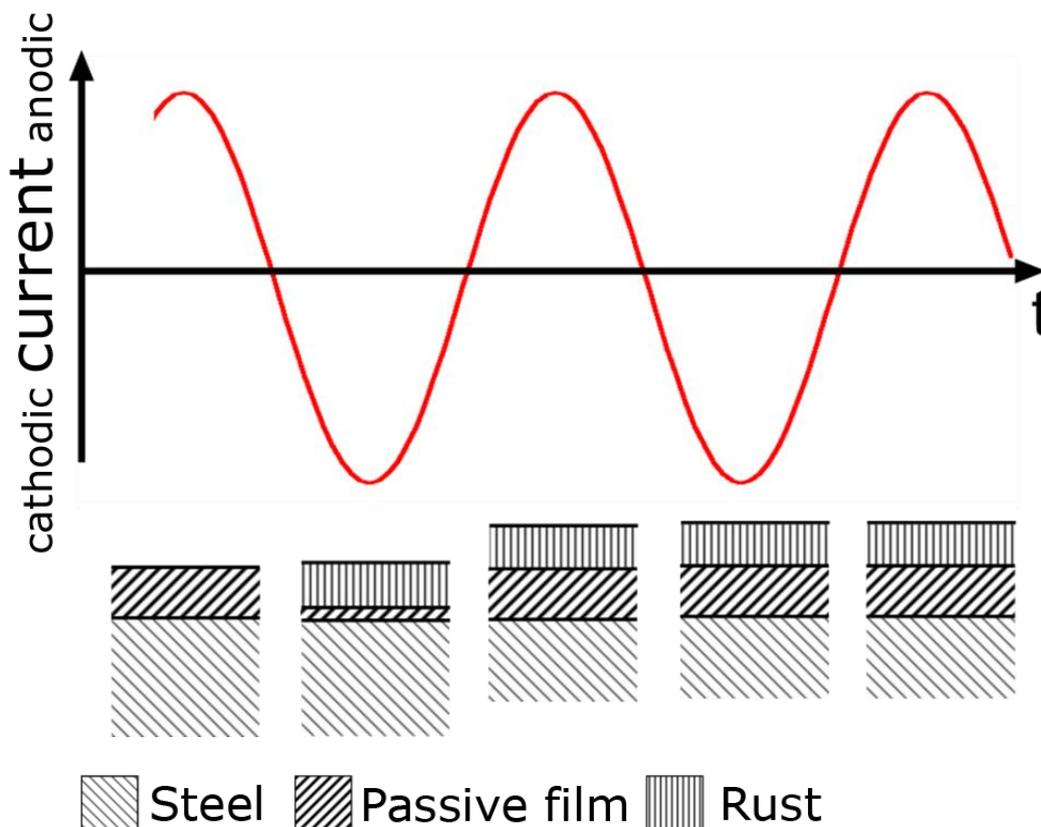


Figure 1: Steel surface in an alkaline environment under the influence of a variable current over time. The formation of a passive film and a rust layer leads to negligible mass loss despite relevant anodic current densities.

This situation now has partly contradictory consequences. The operators of direct current railways are forced to take costly protective measures, while the operators of alternating current railways operate their infrastructure normatively under critical conditions without further protective measures despite of relevant anodic current discharge at 50 or 16.7 Hz. Considering the latest findings, however, it is advisable to carefully examine the processes taking place and to determine the actual corrosion risk.

The information in EN 50162 for the case of cathodically protected pipelines is also contradictory. For example, for non-cathodically protected pipelines, average anodic influences of 100 mV (with a soil resistance of 66  $\Omega$ m) are tolerated. In the case of cathodically protected pipelines, however, no anodic polarization of the IR-free potential is tolerated anodic of the protection criteria in EN ISO 15589-1. The stray current protection measures for cathodically protected pipelines are therefore much more challenging, even though a corrosion protection system is already installed. This problem has been solved pragmatically in ISO 21857. However, a strict application of the classic Faraday model as in EN 50162 is in contradiction to this and leaves the operation of the pipes in a potentially critical situation. However, the approach of ISO 21857 is in good agreement with the model approach shown in Figure 1.

## 2. Measurements and results

### 2.1. Introduction

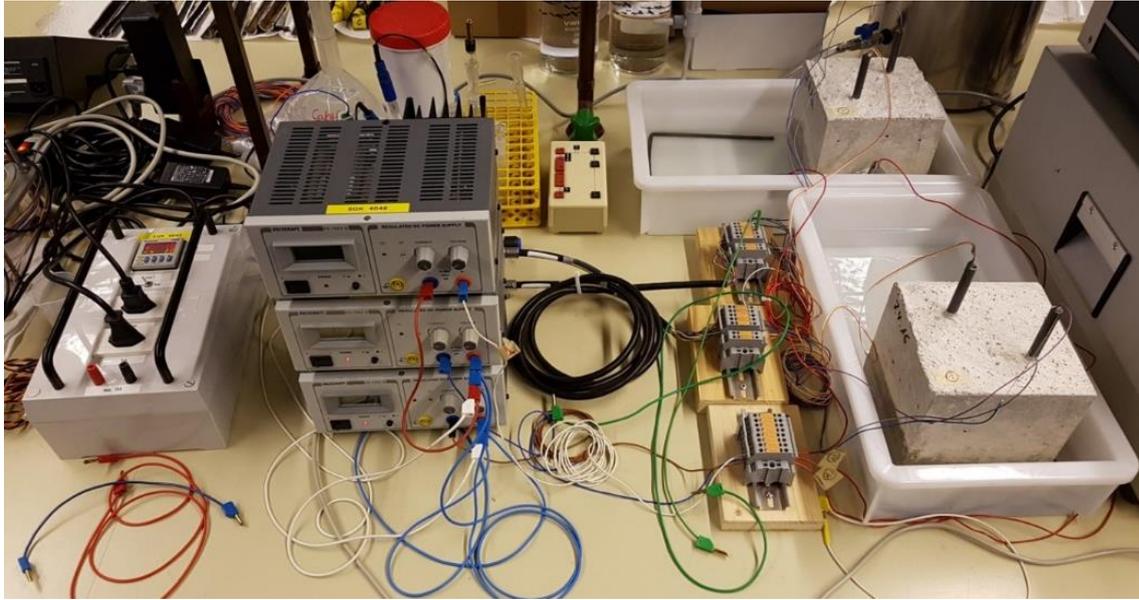
Recent findings on the corrosion of steel in soil as well as the understanding of the mechanistic principle of cathodic corrosion protection have shown the importance of mass transport conditions, pH value, bedding conditions and water hardness. These aspects were specifically considered in the investigations. In addition, the importance of the different redox systems based on iron Fe(0)/Fe(II)/Fe(III), oxygen O(0)/O(II) and hydrogen H(0)/H(I) was considered. Based on present knowledge, these are of central importance regarding the charge transfer through the steel surface and the associated corrosion processes in stray current situations.

Various experiments have been carried out to demonstrate the problem of corrosion of steel influenced by stray currents. In particular, the corrosion of steel in concrete without cathodic protection (CP) was investigated. These tests were intended to investigate how steel in concrete behaves with stray current interference. For this purpose, concrete cubes were equipped with a steel wire  $\varnothing$  0.5 mm as a test specimen. The composition of the concrete cubes with 15 cm edge length is given in Table 1.

**Table 1: Composition of the concrete test specimens**

Volume [l]	Water [l]	Cem II [kg]	Aggregates		
			0-4 [kg]	4-8 [kg]	8-16 [kg]
12	2.176	3.636	11.160	4.687	6.473

The corrosion rate was determined in situ by measuring the temperature-compensated resistance of this 0.5 mm steel wire. It was assumed that a corrosion attack will occur on the whole circumference of the wire and thus the calculated thickness  $d$  [ $\mu$ m] of the specimen corresponds to its radius. The time derivative of the thickness  $d$  [ $\mu$ m] then corresponds to the corrosion rate  $v_{\text{corr}}$  [mm/a]. The test was carried out in parallel with two different settings:



**Figure 2: Test setup of steel in concrete**

Test 1: A constant, anodic stray current was simulated, which led to current leakage at the sample. The potential of this sample was therefore set to different constant values over a certain time. Potentials were set to  $+0.5 V_{CSE}$  and even more positive values.

Test 2: An alternating stray current with cathodic and anodic phases was simulated. For example, the potential was set at  $+1.0 V_{CSE}$  (anodic) for 30 s and following at  $-1.0 V_{CSE}$  (cathodic) for 30 s. Figure 5 shows the potential and current density curve of this experiment. Various combinations of anodic and cathodic potential values were set.

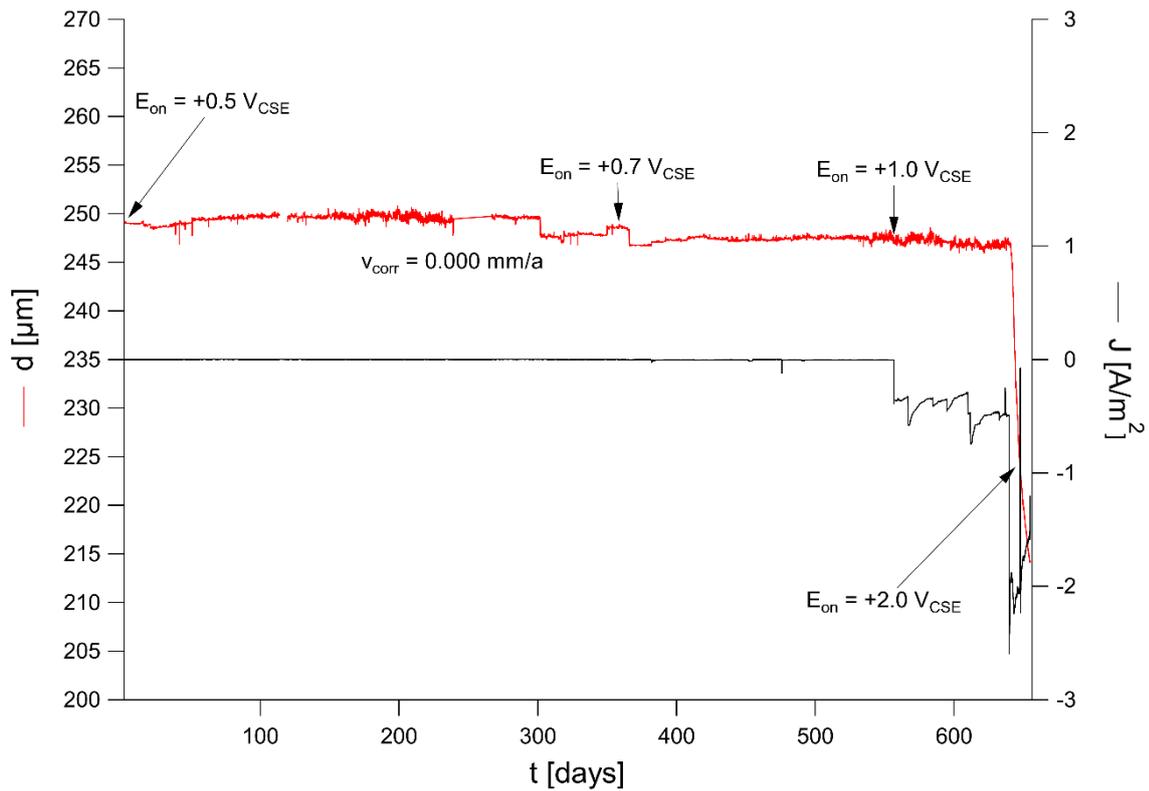
Figure 2 shows the test setup with two concrete bodies, the DC current sources and the switch box for test 2.

## 2.2. Results

### 2.2.1. Time constant anodic interference (test 1)

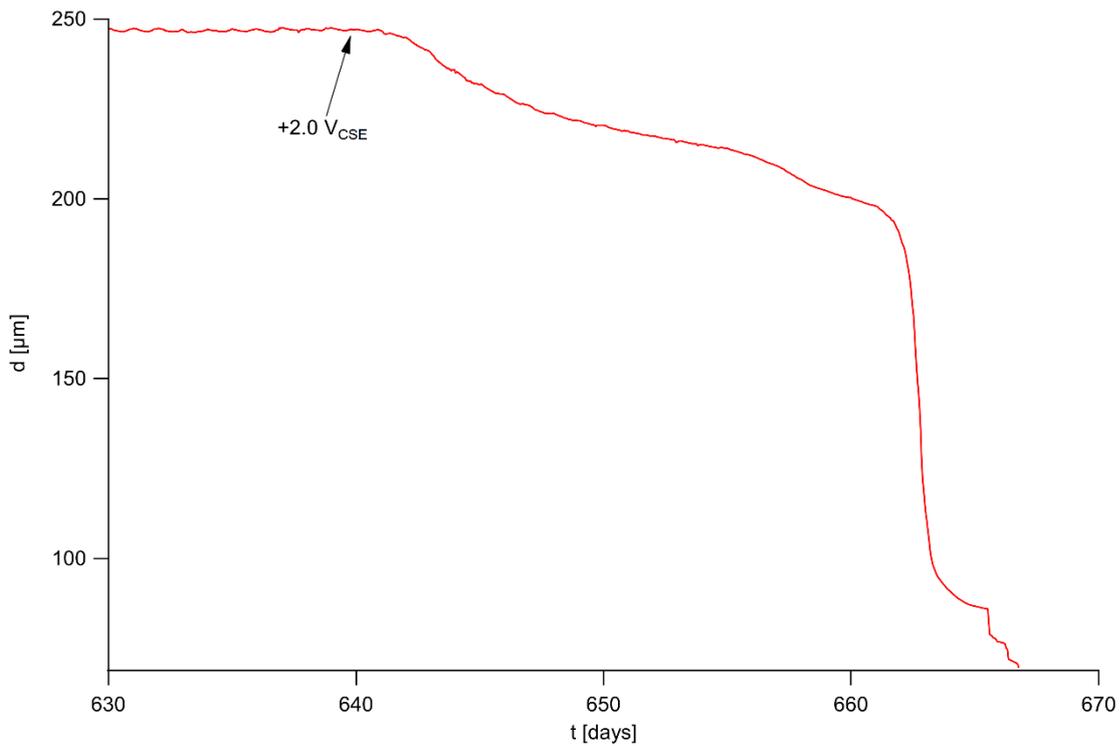
Figure 3 shows the thickness  $d$  of the specimen of test 1 over time. Due to the permanent current leakage, it would have to be expected that the pH value of the alkaline concrete is neutralized over time and the steel loses its passive properties and corrodes. Over time, however, the calculated thickness  $d$  of the sample did not show relevant reduction, meaning there was no corrosion at a constant polarization of  $+0.5 V_{CSE}$ . In fact, only very low anodic current densities of a few  $\text{mA/m}^2$  flew during the period as shown in Figure 3. An overview of all tests with constant anodic current is shown in Table 2. The low current at the on-potential of  $+0.5 V_{CSE}$  is probably the result of a potential still cathodic of the oxygen evolution.

Increasing the potential to  $+0.7 V_{CSE}$  also did not yet lead to a relevant increase in current, as shown in Figure 3. Some acid formation cannot be excluded, shifting the equilibrium potential for the oxygen evolution anodic as illustrated in Figure 9. At constant anodic load, the current will stabilize by itself at a low level. Only at potentials of  $+1 V_{CSE}$  current densities in the range of  $0.5 \text{ A/m}^2$  were observed. In this case, the on-potential was clearly anodic of the oxygen evolution line, which led to correspondingly high anodic current densities. However, even under this condition corrosion did not occur. It must be concluded that despite the pronounced oxygen evolution, the pH value on the steel surface did not drop significantly.



**Figure 3: Calculated thickness  $d$  of the sample during test 1 (red line)**

This is probably due to the migration of hydroxide ions in the electric field to the steel surface. This means that the increased current does result in increased acid formation, but since the current flow is primarily based on the transport of hydroxide ions, it also causes increased neutralization.



**Figure 4: Enlarged period from Figure 3 of the wire thickness after switching to +2 V<sub>CSE</sub>.**

Only when the potential was increased to  $+2 V_{CSE}$  corrosion activated within a short period of time with a very high corrosion rate, as can be seen in Figure 4, which shows the enlarged period on the very right from Figure 3 (after day 640). Based on the available data, it can be assumed that only current densities of more than  $1 A/m^2$  can lead to a sufficient lowering of the pH value on the steel surface in concrete and thus to the initiation of corrosion.

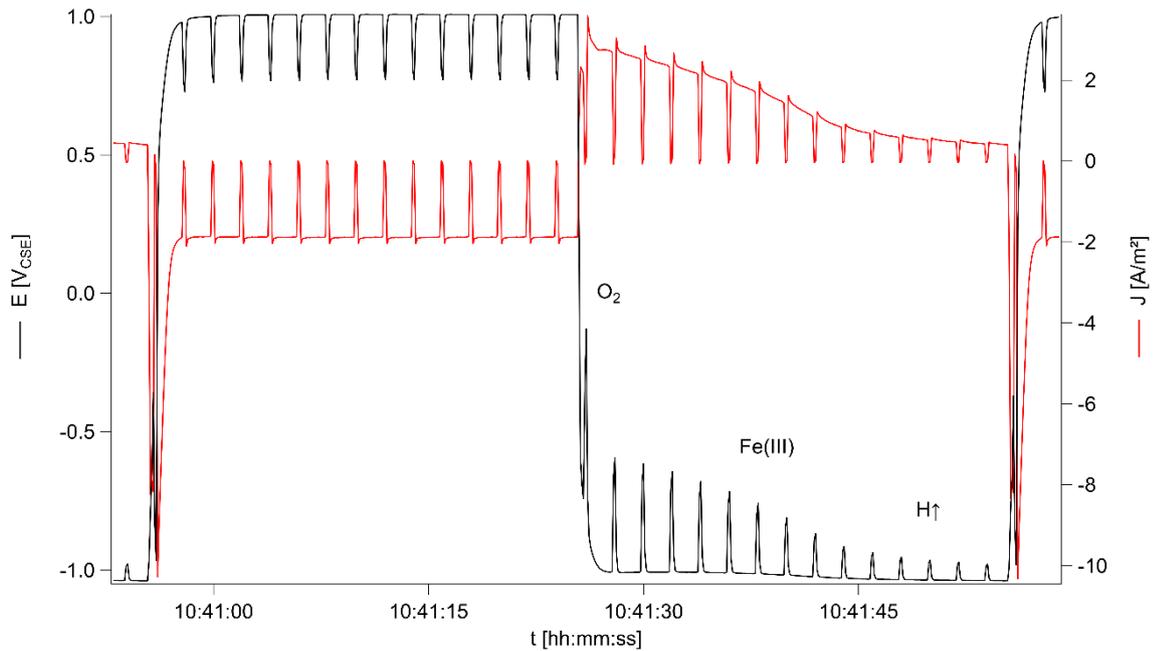
**Table 2: Constant anodic stray current (anodic current with negative sign)**

Potential [ $V_{CSE}$ ]	$J_{a,avg}$ [ $A/m^2$ ]	$E_{IR-free}$	$v_{corr}$ [mm/a]
+0.5			0.000
+0.7	-0.000	0.533	0.000
+1.0	-0.523	0.742	0.000
+2.0	-2.665	0.758	2.283

### 2.2.2. Time-variant anodic interference (test 2)

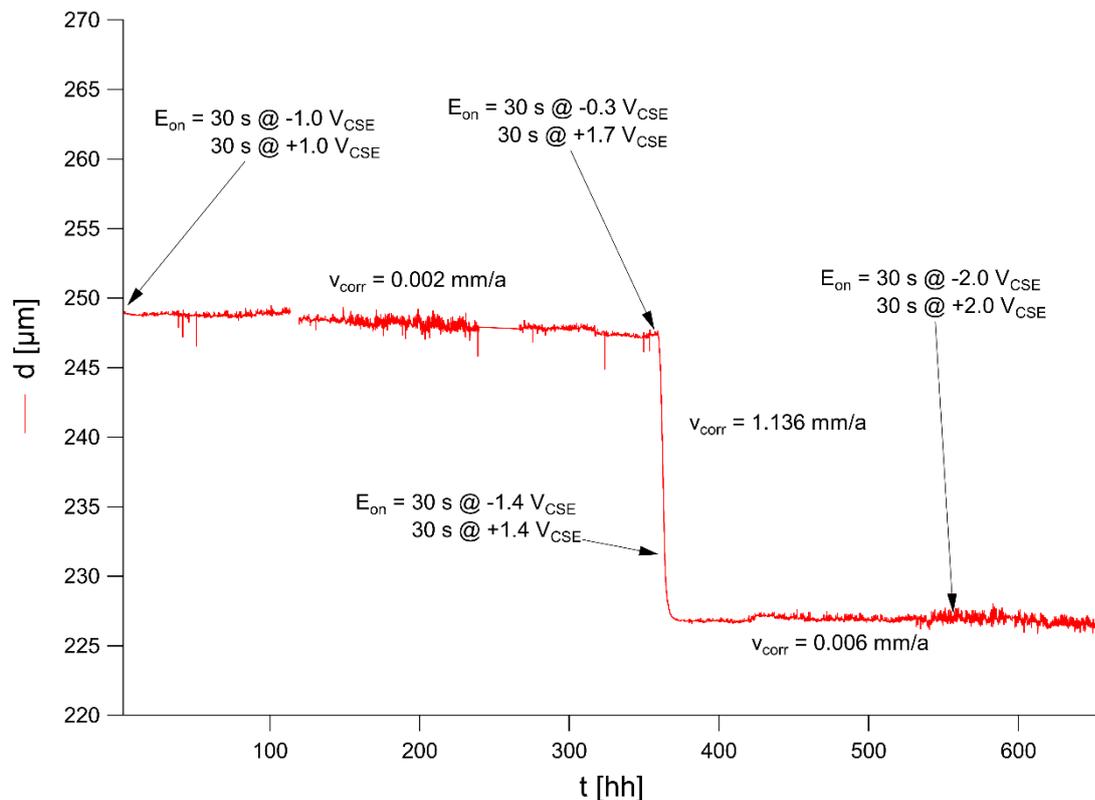
To evaluate the effect of the time-variant stray current, the current was periodically interrupted at the end of an influencing cycle set. In this way, the IR-free potential of the test sample and the associated current within an influencing cycle could be determined. Figure 5 shows the result for an anodic polarization of  $+1 V_{CSE}$  and a cathodic polarization of  $-1 V_{CSE}$ . This curve is typical for an influence variant over time according to test 2. The following conclusions can be drawn from the curve:

- The anodic current densities are significantly higher than  $-1 A/m^2$  and are largely constant over time. The IR-free potential is at about  $+0.6 V_{CSE}$ . This behavior can only be explained by oxygen evolution on the passive steel surface. This means that the anodic current is not consumed for corrosion, but for oxygen formation and acidification. It is to be expected that, in addition to oxygen evolution, oxidation of Fe(II) will also take place within the passive film and any rust layer present.
- The cathodic current is strongly time-dependent, and the IR-free potential also shows a pronounced time dependence within the cycle. This behavior can be interpreted as follows: After switching the current direction, the cathodic current is first used for the reduction of anodically formed oxygen (marked with " $O_2$ " in Figure 5). Its rapid depletion at the steel surface over time leads to an increasing shift of the IR-free potential in the cathodic direction. At potentials of  $-0.5 V$  the reduction of Fe(III) to Fe(II) is occurring (marked with "Fe(III)" in Figure 5) until hydrogen evolution (marked with " $H\uparrow$ " in Figure 5) sets in at  $-0.95 V_{CSE}$ . The decrease of the cathodic current is probably due to the increasing shift of the IR-free potential in the cathodic direction. The decreasing difference between on- and IR-free potential leads to a lower cathodic current.



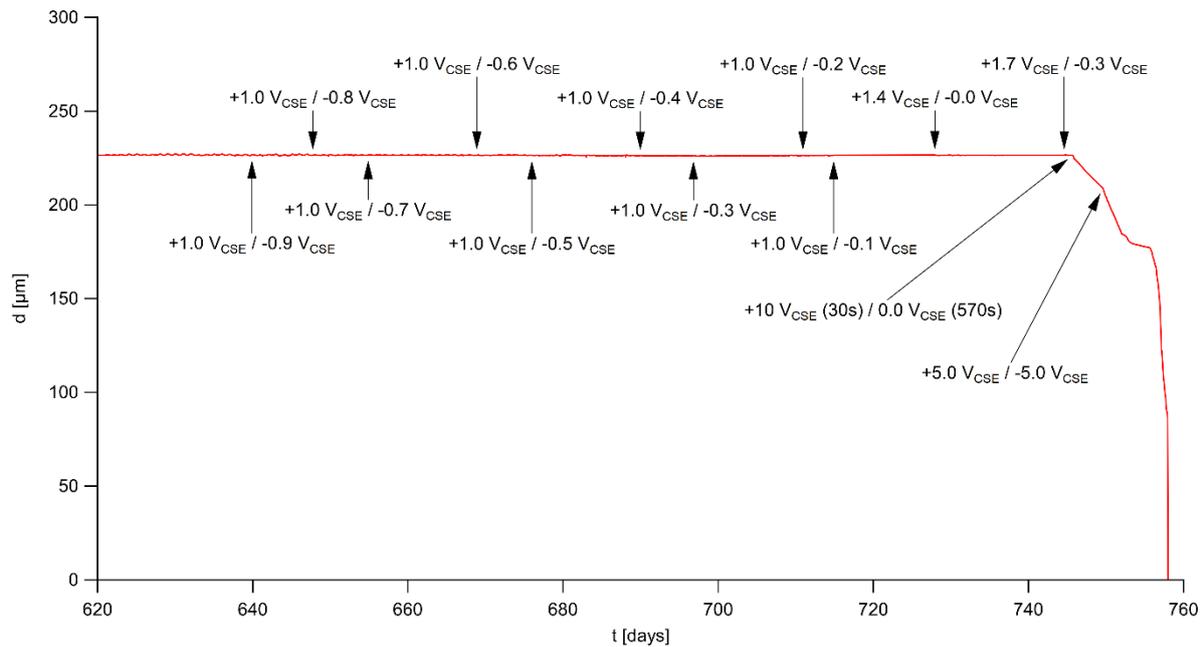
**Figure 5: Potential and current density curve during an influencing cycle in test 2 at test start. During this measurement, the current was also interrupted to measure the IR-free potential.**

This behavior is confirmed in all tests with steel in concrete. An overview of the results is shown in Table 3. The comparatively high anodic current densities are also in good agreement with the data in Figure 3 for a constant anodic influence. It is shown that very large anodic current densities can be absorbed in parallel redox systems other than the reaction  $\text{Fe}(0)/\text{Fe}(\text{II})$  and thus without corrosion of the steel. These are primarily the redox systems  $\text{Fe}(\text{II})/\text{Fe}(\text{III})$  and  $\text{O}(0)/\text{O}(\text{II})$ .



**Figure 6: Calculated thickness  $d$  of the sample during the test 2**

Figure 6 shows the calculated thickness  $d$  of the sample in the test 2 over time with temporally variant stray current influence, each of which was maintained over several months.



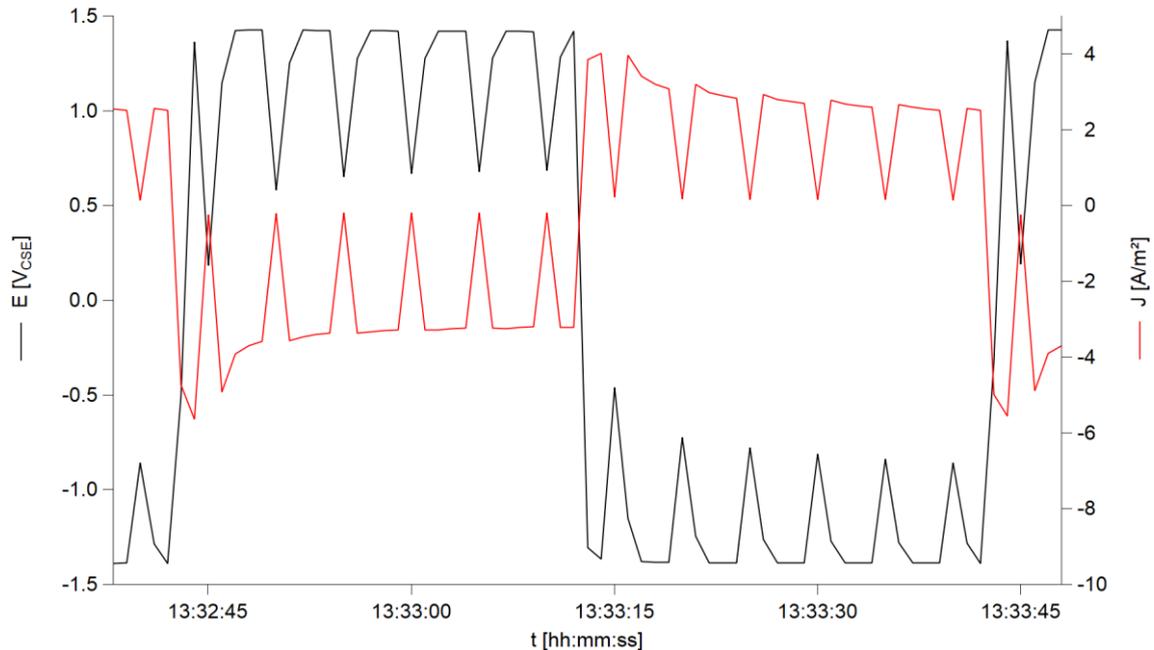
**Figure 7: Final phase of tests with steel in concrete under widely variant conditions.**

Figure 7 shows the results of short-term measurements of one week each. Also, in this case, the anodic current should lead to corrosion of the steel, unless alternative electrochemical reactions can consume the anodic charge. The anodic potential shift due to the stray current was 1 V. However, it was only applied for 30 s at a time, which corresponds to half a period. The other half period was a cathodic influence. Over time, there was no relevant corrosion in the initial phase as the concrete could buffer any acidification.

**Table 3: Time variant anodic and cathodic influence (each 30 s)**

$E_{on}$ [V <sub>CSE</sub> ]	$J_{a,avg}$ [A/m <sup>2</sup> ]	$J_{k,avg}$ [A/m <sup>2</sup> ]	$E_{a,IR-free}$ [V <sub>CSE</sub> ]	$E_{k,IR-free}$ [V <sub>CSE</sub> ]	$v_{corr}$ [mm/a]
+1.4 / -1.4	3.371	2.800	0.684	-0.876	<0.01
+2.0 / -2.0	5.644	3.543	-0.185	-0.716	<0.01
+1.0 / -1.0	0.189	0.157	0.770	-0.977	<0.01
+1.0 / -0.9	0.977	1.130	0.648	-0.540	<0.01
+1.0 / -0.8	0.987	0.966	0.649	-0.516	<0.01
+1.0 / -0.7	1.172	0.881	0.627	-0.400	<0.01
+1.0 / -0.6	0.729	0.703	0.683	-0.349	<0.01
+1.0 / -0.5	0.481	0.704	0.697	-0.301	<0.01
+1.0 / -0.4	0.444	0.667	0.692	-0.188	<0.01
+1.0 / -0.3	0.678	0.470	0.693	-0.091	<0.01
+1.0 / -0.2	0.554	0.390	0.702	0.022	<0.01
+1.0 / -0.1	0.666	0.429	0.707	0.121	<0.01
+1.0 / 0.0	0.643	0.393	0.709	0.232	<0.01
+1.4 / 0.0	1.263	0.473	0.678	0.295	<0.01
+1.4 / -0.7	1.783	0.999	0.644	-0.195	<0.01
+1.7 / -0.3	2.487	0.692	0.449	0.010	1.136
+10 (30s) / 0.0 (570s)	94.926	0.000	-	-	1.534
+5.0 / -5.0	27.296	6.482	-	-	3.497

To generate more severe conditions in test 2, within a cycle the cathodic potential was raised to  $-0.3 V_{CSE}$  and the anodic potential to  $+1.7 V_{CSE}$ . Since the latter adjustment led immediately to severe corrosion, the setting was adjusted to  $-1.4 V_{CSE}$  and  $+1.4 V_{CSE}$  only 5 days later, which in turn led to a reduction of the corrosion rate to negligible values within a short time. This was despite anodic current densities in the range of  $3 A/m^2$  (Figure 8).



**Figure 8:** Potential and current density progression during a cycle in test 2 after adjusting the potentials to  $\pm 1.4 V_{CSE}$ . During this measurement, the current was also interrupted to measure the IR-free potential.

### 3. Discussion

#### 3.1. Introduction

Based on the present findings on how stray currents work, new criteria for assessing the influence of stray currents were developed. These are confirmed by extensive laboratory investigations and the available literature. The pH and a net cathodic current density were identified as crucial parameters for buried structures [7].

In the case of steel in concrete, the increased pH value at the steel surface is a consequence of the alkalinity of the concrete and not of an externally applied protective current. It has been found that in the case of metallic structures embedded in concrete, where the influence varies over time, an assessment of the corrosion situation based solely on anodic excursions without taking into account the cathodic influence leads to incorrect assessments. The passivity prevents corrosion even with strong anodic influences. In this sense it would be possible to relax the present protection criteria for steel in concrete.

## **3.2. Protection criteria for steel in concrete**

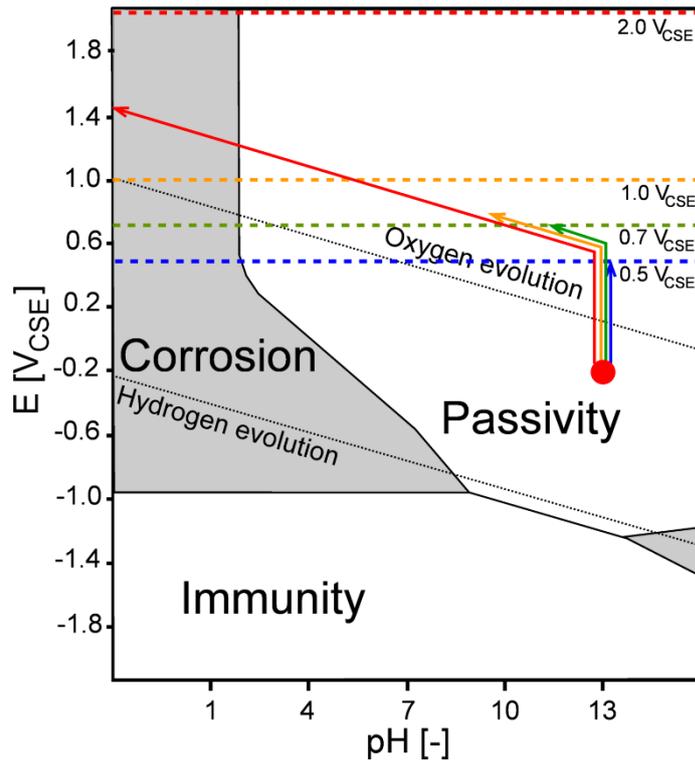
### **3.2.1. Introduction**

It was shown that the protective effect of the CP on buried structures is based on an increase in the pH value and the resulting passivation. Due to the alkalinity of the pore solution, the pH value in concrete is between 12.5 and 13.5, which means that conditions comparable to those for steel under effective CP are present. Thus, in concrete, a comparable argumentation can be used regarding the effect of stray current interference as detailed in [7]. If the pH value is increased and passivity is present, the anodic currents will not lead to corrosion. Rather, the charge is consumed for alternative oxidation reactions, that are taking place in parallel redox systems. The results of the investigations performed are discussed in the following, whereby a distinction is made between time constant and time-variant anodic influence.

### **3.2.2. Time constant anodic interference**

Time constant anodic influences usually originate from cathodically protected systems. Particularly in the case of wall penetrations of pipelines in combination with a damaged coating, an anodic influence on the reinforcement can hardly be prevented. The measurements performed have shown that even very strong time constant anodic influences of +0.5 and +0.7  $V_{CSE}$  do not lead to corrosion. This is in good agreement with the associated low anodic current densities observed. However, the question arises why these current densities are only that low. Based on the available information, the effect can only be explained as follows:

The IR-free potentials are clearly anodic from the equilibrium line for oxygen evolution. Therefore, high anodic current densities are unavoidable at a strongly increased pH value. Over time, however, these anodic current densities inevitably lead to a certain reduction in the pH value and an accumulation of oxygen on the steel surface. Both effects cause a shift of the equilibrium potential for oxygen evolution in the anodic direction (blue and green arrows in Figure 9). This means that the reaction products lead to a reduction of the overvoltage for the anodic reactions and thus to a self-limitation of the current. This effect is comparable to the protective effect of an on-potential of -1.2  $V_{CSE}$  with respect to AC corrosion [8]. An increase of the pH value leads to a shift of the IR-free potential in the negative direction along the hydrogen evolution line. As soon as this has reached a value of -1.2  $V_{CSE}$ , no further current will flow. This on-potential consequently leads to a self-limitation of the cathodic current. The further current flow is only controlled by the surface pH that will establish as a function of hydroxide ion generation and their migration into the surrounding soil. The situation in the anodic direction is, hence, comparable in some ways. The anodic current leads to a reduction of the pH value and thus also to a self-limitation of the current in the case of +0.5 and +0.7  $V_{CSE}$ .



**Figure 9: Pourbaix diagram, graphically explaining the effect of the anodic current self-limitation.**

For the anodic influence of  $+1.0 V_{CSE}$  a significant increase in current, but still no corrosion was observed. This effect can be explained with the effective buffer capacity of concrete that prevents a sufficient decrease of the concrete pH. As illustrated with the orange arrow in Figure 9 there remains a certain overpotential due to the increased surface pH that maintains a decrease of the anodic current density in the range of  $-0.5 A/m^2$ . Evidently this current density is insufficient to neutralize the alkalinity of the concrete and cause the breakdown of passivity. This breakdown of passivity only occurs at current densities of  $-2.8 A/m^2$ , resulting in corrosion rates of  $2.2 mm/year$ , which is well expected based on Faradays law. In these cases, no relevant parallel oxidation reactions are taking place due to polarization of the steel into the corrosion domain, as shown with the red arrow in Figure 9.

This description corresponds well with the observations. However, there is an additional aspect concerning the effect of an extensive anodic influence. Under cathodic corrosion protection, it is known that even lowest cathodic current densities are sufficient to raise the pH value significantly, as long as a good bedding is present, and the accumulation of alkalinity is ensured. In fact, ideal bedding conditions are present in concrete, which prevent any convection effects. The reaction products can therefore accumulate very easily. The question therefore arises as to why no corrosion was triggered even over very long test periods of 12 months under continued anodic polarization. This is probably due to another effect which was already observed during cathodic over-polarization [9]. Under continued cathodic current no unlimited increase in pH was observed. The higher cathodic current density results in more hydroxide ion production, but the associated higher current also causes accelerated migration. As the hydroxide ions have a very high concentration and a very high mobility, the cathodic current flow will primarily push them away from the steel surface by migration. The increased current thus leads to an increased pH value, but it also carries away the involved hydroxide ions faster. At high pH-values this results in a limitation of the achievable pH-value at the steel surface. In the case of anodic polarization, certain analogies can be expected. In the strongly alkaline environment of concrete, the anodic current flow should

primarily lead to the migration of hydroxide ions towards the steel surface. This has the consequence that acid formed on the steel surface due to the anodic current will be neutralized by the migration of hydroxide ions. This is possible as long as the concrete can maintain its high alkalinity and the transport processes. Consequently, it is expected, that this neutralization of acid is only possible at low anodic current densities in non-carbonated alkaline concrete. This low current density is expected to be in the range of up to  $1 \text{ A/m}^2$  based on the obtained results.

In concrete, it was shown that the shift of the potential in anodic direction due to passivity does not lead to corrosion as long as the pH value is sufficiently high. However, this potential shift can lead to pitting corrosion in steel. As soon as the steel potential is anodic of the critical pitting potential, pitting corrosion and strongly accelerated local corrosion must be expected. This means that the anodic potential shift in chloride loaded concrete can lead to relevant local corrosion as soon as an increased chloride content is present on the reinforcement surface. The positive effects observed in these experiments are partly the result of the absence of any chloride contamination.

### 3.2.3. Time variant influence

Interestingly, with constant anodic influence, only negligible corrosion was found in alkaline concrete with low chloride content up to a critical anodic potential higher than  $+1V_{\text{CSE}}$ . In case of time variant influence, however, the situation is significantly worse, as increased current densities occur in both the anodic and cathodic direction. The question arises which redox system allows this charge to pass through the steel surface. It has been shown for buried structures that the charge is transferred via the redox system Fe(II)/Fe(III). In concrete, it was shown that the redox system O(II)/O(0) is also available. This means that anodic current is consumed also for oxygen generation and cathodic current for oxygen reduction.

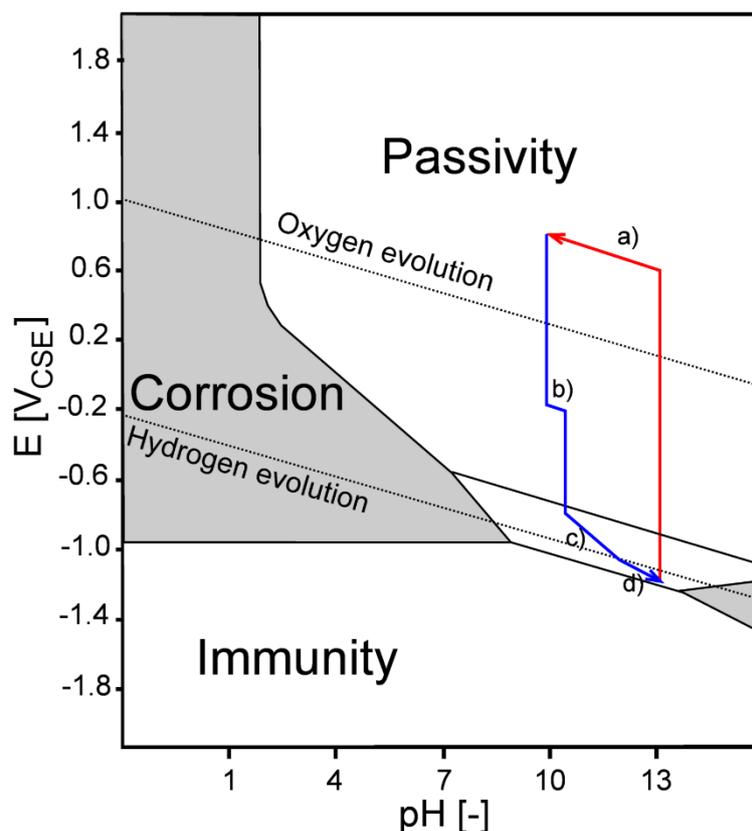


Figure 10: Pourbaix diagram, graphically explaining the time evolution of the IR-free potential in Figure 5.

The time evolution of the IR-free potential in Figure 5 is explained in Figure 10 by means of the Pourbaix diagram. During the anodic polarization phase of the cycle (a) the IR-free potential raises up to  $+0.75 V_{CSE}$  where oxygen evolution takes place. In the subsequent cathodic polarization phase first oxygen is reduced (b). Within the potential range of about  $-0.5 V_{CSE}$  and  $-1.0 V_{CSE}$  the reduction of Fe(III) to Fe(II) is taking place (c). Further cathodic current is then consumed for hydrogen evolution (d).

The good availability of water leads to the very high currents. In principle, this would not be critical from a corrosion point of view. However, the high currents can lead to locally reduced pH values with heterogeneous distribution of the current densities. The following situation is conceivable, especially with locally strongly increased anodic current densities: Initially the pH-value decreases locally. This locally increased anodic current density also leads to increased migration of hydroxide ions to the steel surface and diffusion will also limit the lowering of the pH value. However, it must be assumed that there is a critical time averaged current density at which these compensation effects are too slow to prevent acidification. In this case corrosion and thus greatly increased corrosion will occur as demonstrated with time averaged anodic current densities above  $2 A/m^2$ .

This effect is particularly pronounced when, the time averaged anodic current density is higher than  $1 A/m^2$ . In this case, a local reduction of the pH value and thus, even in absence of chloride contamination, the occurrence of corrosion is expected.

#### 4. Conclusions

In the performed tests, corrosion did not occur in any case if the average anodic influence was less than 500 mV. This is true for constant anodic polarization as well as for time variant anodic influences. Based on these results, the limit value of an average 500 mV anodic influence as it was specified in the SGK guideline C3 from 2001 for steel in chloride-free and non-carbonated concrete can be confirmed. The problem with this threshold, is the restriction to alkaline concrete that is not contaminated with chloride.

While this conclusion is correct for the given experimental parameters, the obtained results indicate that the underlying damage mechanism is closely related to the acidification of the concrete at the steel surface as a result of the time average anodic interference. Based on the obtained results this acceptable level of average anodic current density is in the range of  $1 A/m^2$ . Based on the presented argumentation this current density is expected to depend on the pH of the surrounding concrete and may decrease in case of less alkaline cement binders.

The problem with the restriction to chloride-free and non-carbonated structures is that it is not easily possible to confirm these conditions without further investigations. In principle, however, it can be assumed that both carbonation and chloride contamination are rather unlikely or at least limited to a few components in railway systems. This is especially true for anchorages or foundations. It can generally be assumed that chloride contamination and carbonation are of minor importance in railway structures if the appropriate standards are correctly implemented and the corresponding exposure classes are taken into account. Therefore, it can be concluded that the introduction of the former limit value of 500 mV for anodic stray current interference of the SGK guideline C3 is quite appropriate.

However, if chloride contamination or carbonation is expected or confirmed by measurement, the limit value of EN 50162 of 200 mV for the average anodic influence on steel in concrete shall be applied.

## 5. Literature

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