

Recommended practice for reporting experimental data produced from studies on corrosion of steel in cementitious systems

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Received: 02 April 2019 / Accepted: 01 July 2019 / Published online: 5 July 2019

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Abstract

Experience has shown that many aspects of experimental design for studying steel corrosion in cementitious systems may significantly influence the obtained results. In the absence of standardized methods to study steel corrosion in concrete, researchers usually define their own test setups, which partially explains the large scatter and uncertainty in the aggregated published data. When the details of these setups are not provided adequately, experimental results cannot be interpreted in a wider context. Unfortunately, many scientific publications lack important experimental details. Therefore, this paper aims at improving the quality of reported experimental details, observations, and data in scientific publications, and raising awareness for relevant issues to improve the quality of research in the field. To this end, this paper provides a list of experimental details that have been found important by many decades of research, and which are, thus, recommended to be considered in conducting and reporting laboratory studies involving corrosion of steel embedded in cementitious systems. Finally, we propose a checklist for reporting experimental data in scientific publications.

Keywords: Reinforcement; Steel; Rebar; Corrosion; Concrete; Pore solution; Testing; Chloride

1 Introduction

The number of peer-reviewed research publications, and their citations, on corrosion of steel in cementitious systems have increased exponentially in the past three decades, as shown in Fig.1. The creation of new knowledge during this period raised the awareness of the subject, which resulted in a renewed understanding of the problem and new developments for its assessment and mitigation. However, this increased interest also created major challenges for both the research community and the practitioners because of the inconsistencies in the design of experiments and the reporting of experimental data.

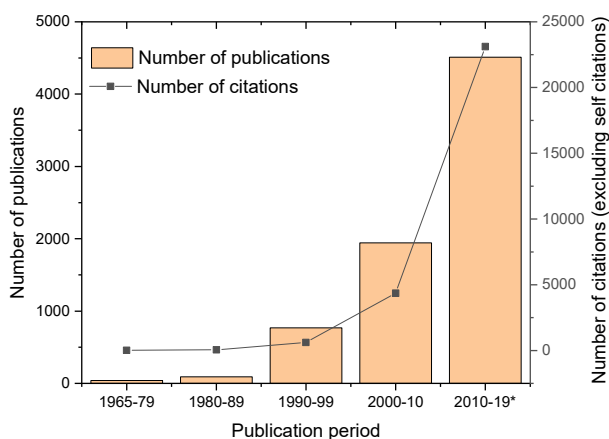
Many aspects of experimental design for studying steel corrosion in cementitious systems can significantly influence the obtained results. Thus, appropriate reporting of

experimental details is critical to facilitate correct interpretation of the data by the research community. For example, Angst et al. [1] showed that 60% of surveyed peer-reviewed papers in the literature did not report the rebar type (smooth vs. ribbed) in their experiments. Similarly, about 40% did not report the steel surface condition (as received vs. sandblasted vs. polished, etc.), although it is well known that this affects the result of corrosion studies significantly [2]. The lack of experimental detailing in scientific publications – including recent ones – hampers the interpretation of results from different studies. Rather frequently, interpreting of experimental data from certain studies can be difficult when comparing and reviewing literature because important details of the conditions under which the results were produced are not reported. This unsatisfactory situation highlights the need and constitutes the motivation for our contribution.

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Another challenge in the study of corrosion of steel in concrete originates from the absence of standardized test methods specifically developed for the problem. In the absence of these standardized methods, researchers define their own test setups, and when the details of these setups are not provided adequately, experimental results cannot be interpreted in the context of a wider literature. The same issue is also partially responsible for the large scatter and uncertainty in the reported data. For example, it is well documented that the reported critical chloride thresholds in the literature cover a wide range: thresholds represented as total chloride content from experiments with steel embedded in cement-based material in laboratory conditions vary between 0.04 and 8.34% mass of the binder [1]. This scatter is related not only to the physics of the problem, but also to the experimental setup and interpretation.

This paper aims at helping researchers in this field to (1) identify the most relevant parameters to be addressed in scientific publications on the topic; (2) improve the consistency of experimental observations and data; (3) raise awareness for relevant issues to improve experimental setups.



(*) 2019 data contain only partial information from January.

Figure 1. The number of publications on corrosion of steel in concrete in recent decades. The data were obtained using a Boolean search on the Web of Science (ISI) with the following criteria for the title of the publication: (“corrosion”) AND (“concrete” OR “mortar” OR “paste” OR “pore solution” OR “cement” OR “cementitious”) AND (“steel” OR “rebar” OR “reinforcement” OR “reinforcing bar”).

2 Experimental details to be considered in studies of corrosion of steel in cementitious systems

2.1 Metals

2.1.1 The metallurgy

Several reports have indicated that both the chemical composition and the microstructure of the reinforcing steel have an impact on its corrosion performance, even within the type of steels typically denoted “mild steel” or “carbon steel” [3-8]. Thus, it is important to adequately report the relevant information.

Carbon steel reinforcing bars (black rebar) are generally arc furnace products from recycled iron and steel artefacts. ASTM has two standards for steel reinforcement that are commonly used that require minimum compositional requirements.

ASTM A615 [9] covers conventional carbon steel bars of various grades and specifies only a maximum phosphorous content. ASTM A706 [10] applies to high strength and/or weldable bars and specifies maximum compositional limits on carbon, manganese, phosphorus, sulphur and silicon. In Europe, reinforcing steel is classified by EN 10080:2005 [11] into strength grades with compositional limits on carbon, phosphorus, sulphur, copper, and nitrogen. In a similar fashion, the compositional requirements for stainless steel and low carbon chromium steel are provided in ASTM A955/A955M [12] and ASTM A1035/A1035M [13], respectively.

Because of the limited requirements and the assumption that the minor constituents have little influence on corrosion, the carbon steel chemical composition analysis is rarely provided in publications. Reporting the standard that governs the steel provides the minimum information related to the general composition of the metal being studied. However, it is recommended that both the composition and the strength grade be documented in publications. This would allow any influence of these factors on conflicting results to be identified. This information is of particular importance for metals that do not follow a published standard. Additional information on the microstructure, such as phases present, grain size, etc. can be included if relevant to the study being conducted.

2.1.2 Steel surface condition

The metal surface condition can significantly influence the corrosion test in simulated pore solutions and in cement paste, mortar, and concrete [2, 14-25]. Thus, it is essential to report the surface condition of the metal, which may include the following: sandblasted, milled, polished (to what degree), pickled (with what method), washed with acetone (degreased), as-received (with mill-scale or pre-existing rust scales, extent if known).

It is also critical to report the exposed surface area and the part of the rebar that is exposed (cf. section 2.3.2). In most studies, this is the surface of rebar, but occasionally coupons fabricated from rebars or other base steels were used; i.e., machined or cut surfaces.

2.1.3 Rebar end protection

Rebar ends, whether they protrude from the specimen or not, present heterogeneity in material properties (e.g. cut surface) and exposure conditions (e.g. in terms of oxygen, chloride and moisture exposure). To avoid inhomogeneity and to limit the exposed surface to a pre-defined length, several methods have been used to shield the rebar ends, including taping and/or epoxy coating. However, this presents a risk for crevice corrosion under the shielding as shown in Figure 2.

A number of researchers have addressed the rebar end protection issue with different methods that have unique advantages and challenges [14, 26-29]. Thus, it is important to report rebar end protection measures used in detail. As it will be discussed in Section 2.6, the appropriateness of these measures needs to be confirmed during the autopsy stage of the experiments.

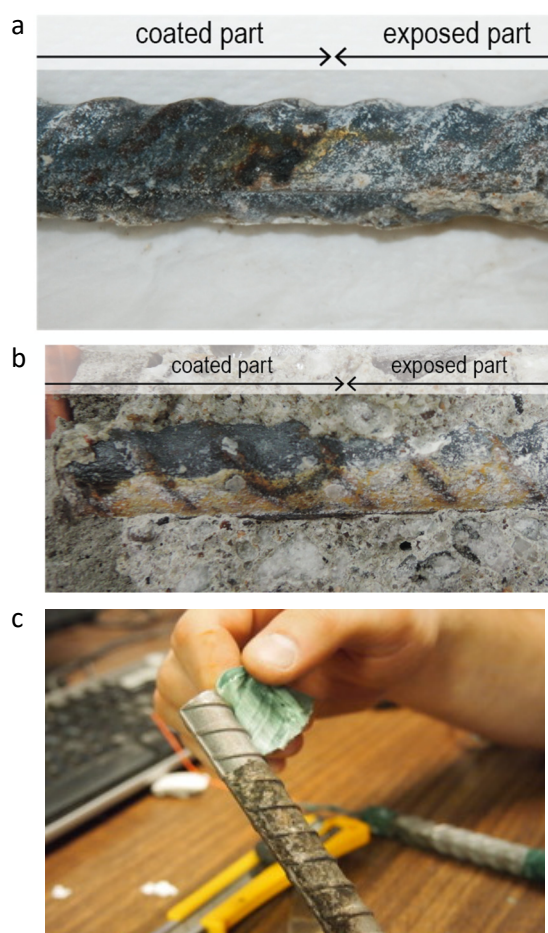


Figure 2: Crevice corrosion under rebar end coating (a) extracted rebar, (b) rebar in concrete. (Coating was removed before photographs were taken), (c) UNS 24100 stainless steel rebar after removal from chloride contaminated concrete and removal of the lacquer and shrink-fit end coating illustrating the absence of crevice corrosion. (Photos in (a) and (b) are the courtesy of U. Angst; photo in (c) is the courtesy of P. Loudfoot).

2.2 Cementitious systems (concrete, mortar, cement paste)

2.2.1 Mixture proportions

The composition of cementitious systems establishes the environment for an embedded metal and is widely known to significantly impact migration of ions, their chemical and physical binding, and the electrochemical reactions at the steel-concrete (or mortar) interface [30]. Chemical and physical properties of constituent materials, as well as compositional proportions, play important roles in characterizing the matrix. Thus, it is important to report the following: (i) material types (cement, supplementary cementitious materials, aggregates, water, admixtures and other additives); (ii) parameters associated with admixtures as applicable (general chemistry, ionic contribution, etc.); (iii) general mineralogy and conditioning of aggregates (iv) water-binder ratio (w/b); (v) characteristics of specialty materials (fibres, etc.) and (vi) proportions of all materials, including air content (if applicable). Certifications and manufacturer-generated test reports with physical and chemical properties of cementitious materials and aggregate may be relevant to studies and, thus, included for possible future review by other

researchers. For some studies, it may be necessary to determine and report physical and chemical properties (e.g. fineness and composition) of specific cementitious materials, admixtures, or other constituents.

2.2.2 Casting parameters

Casting direction influences a number of characteristics, including direction of plastic settlement, orientation of bleed water channels, concrete surface characteristics, and aggregate and reinforcing steel-concrete interface characteristics [31-33]. These factors can impact corrosion study results; therefore, it is critical to report the casting direction with respect to the orientation and location of reinforcing steel.

It is well established that voids at the surface of reinforcing steel, such as those created by poor or improper consolidation, can be initiation sites for corrosion [31]. Poor consolidation might be a result of inadequate workability of concrete. Furthermore, surface density, presence of form-release agents or other materials on surfaces, and voids at formed surfaces exposed to test solutions can affect ingress of exposure solution and, in some cases, electrochemical measurements.

Implementation and reporting of the workability of concrete (e.g. slump, flow, slump flow, or other relevant properties), as well as consolidation and finishing techniques provides affirmation that a homogeneous steel-cementitious material interface was achieved and voids have been purged to the levels expected for the utilized method. Therefore, consolidation method (e.g. internal vibration, external vibration, tamping, use of self-consolidating concrete, etc.), finishing techniques for unformed surfaces, type of form release agents if applicable, and any additional methods to prepare concrete surfaces (e.g. grinding, cutting, polishing, etc.) are important to report.

2.2.3 Curing details

Curing affects concrete quality and the ability to develop potential properties and surface characteristics. Therefore, it is necessary to report curing conditions (or the lack thereof): duration of curing, surfaces subjected to curing, curing temperature, type or combined types of curing methods with applicable reference standards (ponding, submersion, moist/fog room, wet absorptive material, plastic sheet material, evaporation retarder, curing compound, steam, etc.), and any buffering chemicals, e.g. $\text{Ca}(\text{OH})_2$, added to curing solutions. Any differences in curing regime between corrosion test specimens and companion specimens made for other supporting tests should be reported. The storage conditions of specimens between the end of the curing period and the initiation of testing is also relevant as this can have a significant influence on the moisture condition of the specimen.

2.3 Experimental and specimen design

2.3.1 Experimental design

Corrosion is a stochastic process. Therefore, the validity of the research outcomes is related to the number of replicate specimens tested in an experimental program. ASTM E122 [34] document provides guidelines for estimating specimen

size of populations with normal and skewed distributions. Further guidance to select an adequate number of specimens can also be found in [35, 36], where poor reproducibility of corrosion test results from a low number of specimens and small specimen dimensions was addressed with probabilistic considerations. At the minimum, reporting the number of test specimens for each treatment evaluated in a study, the statistical analysis performed on the obtained data, and the validity of the underlying assumptions of performed statistical analysis is important to justify the conclusions of corrosion studies.

2.3.2 Specimen design

A wide range of specimen designs has been used to assess corrosion performance. These specimens have ranged from lollipop specimens (steel embedded in a cylindrical mortar or concrete specimen) [37] to larger concrete slabs [38, 39]. The specimen size is an important, but often underrated, parameter that should receive careful attention [35, 40-42]. Important aspects considered during the specimen design include the depth of concrete cover, the geometry of all involved exposed steel electrodes, and others. In the case of macro-cell test setups, also the anode to cathode area ratio is necessary for interpretation of results. These factors can influence the type of corrosion, time to corrosion initiation, the rate of corrosion propagation, and the amount of chlorides required to initiate corrosion. Because of this, it is recommended that researchers provide specific details of the specimen design and dimensions, preferably with an engineering drawing or an adequate schematic diagram identifying important features and dimensions of the test setup. Fig. 3 shows an example of such a figure.

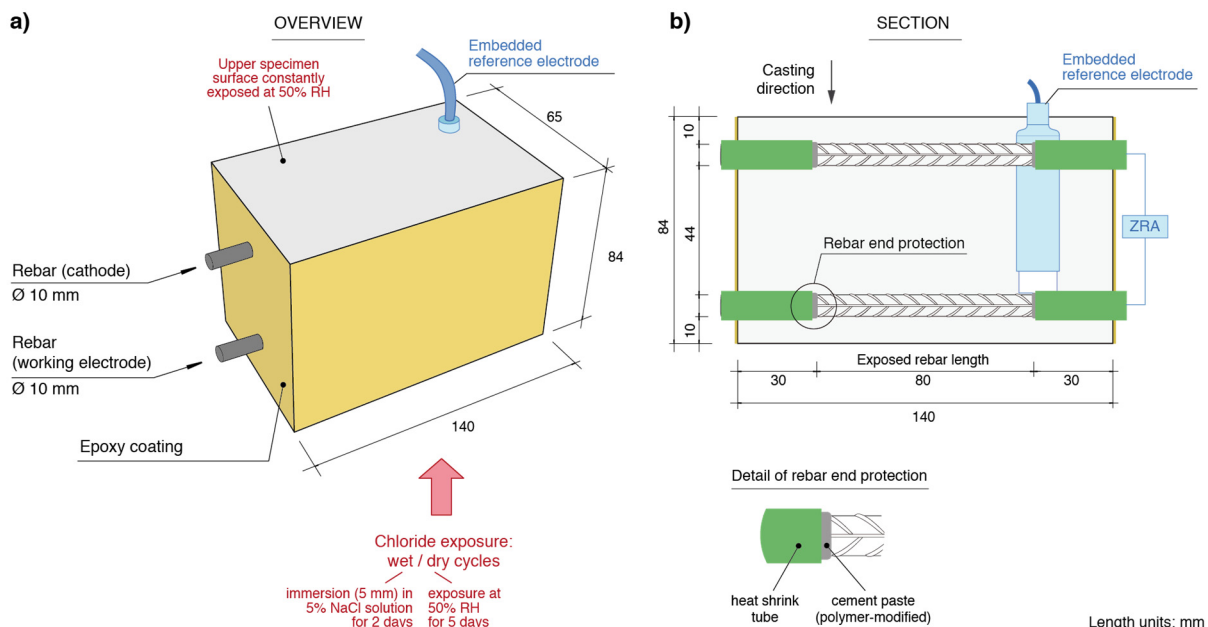


Figure 3: Example of a drawing of the specimen showing all relevant geometrical dimensions, including details about the exposure conditions and the electrochemical instrumentation. a) overview, and b) section. Yellow indicates the epoxy coating, red the exposure conditions, green the rebar end protection measures, and blue electrochemical measurement instrumentation (ZRA = zero resistance ammeter). (Courtesy of U. Angst)

2.4 Electrochemical and electrical measurements

Electrochemical and electrical measurements are typically used to characterize the corrosion state (e.g. passivity vs. active corrosion), to identify active corrosion onset and to quantify the rate of the corrosion process [43]. Many of these techniques are well established in traditional corrosion science textbooks [44] and in standard procedures [45-49].

However, adopting them to corrosion studies of metals embedded in concrete may require special attention [50-56]. Due to the complexity and the controversial discussions in the field related to certain aspects, we cannot give specific advice here. However, to facilitate interpretation of literature results, we recommend that researchers consider the following when planning and documenting electrochemical and electrical measurements in concrete.

2.4.1 Electrodes and electrode setup

It is essential to specify the type of reference electrode used and to include this information whenever reporting measured potentials such as in graphs or in tables. The counter electrode material, size and shape should be provided. Additionally, the electrode geometry and arrangement are relevant, particularly the positions of the reference electrode, the working electrode, and the counter electrode with respect to each other. This is because the geometrical configuration in the three-electrode-setup affects the measured response upon electrochemical excitation [55, 57].

2.4.2 Half-cell potential measurements

Half-cell potential measurements can be influenced by the position of the reference electrode, particularly of those positioned on the concrete surface [54]. It is thus recommended to detail the exact location of the reference electrode, how electrolytic contact was established to the concrete, the concrete cover thickness, and moisture condition of the concrete cover. Additionally, it should be noted that ASTM C876 criterion for 90% probability of corrosion [58] is not always applicable to laboratory conditions and is not applicable at all to coated or alloyed steels [59, 60]. Alternative approaches to distinguish between active corrosion and passive state based on potential measurements were suggested [61, 62]. The particular method and limiting criteria used to characterize corrosion are important to report.

2.4.3 Potentiodynamic and galvanodynamic scans

Sweep or scan rates in potentiodynamic / galvanodynamic polarization tests are known to affect the obtained results [56, 63, 64]. Thus, both for stepwise scans and continuous sweeps, the scan rate (sweep rate, e.g. in mV/s) must be reported, in addition to the extent of the potential excursions from the open circuit potential (for both linear polarization measurements (LPR) and cyclic polarization curves). Moreover, it is crucial to detail if (and how) corrections for the iR drop were made [57], because this may considerably affect the interpretation of the obtained polarization resistance results, Tafel slopes, etc. – especially in a highly resistive environment such as cementitious materials. The potential range over which the Tafel slopes are measured should also be reported.

2.4.4 Electrochemical impedance spectroscopy (EIS)

To facilitate the interpretation of EIS measurements in concrete, it is advisable to report the applied voltage amplitude, frequency range, and the number of measurements per decade.

2.4.5 Macro-cell or galvanic current measurements

If measurements of macro-cell or galvanic currents are not carried out with zero-resistance ammeters, but by measuring the voltage drop across shunt resistors, it is essential to detail the used shunt resistor (in terms of Ohm). This is because the shunt resistor may influence the current flow, depending on its magnitude with respect to the ohmic resistance in the galvanic cell.

2.4.6 Electrical concrete resistivity

Electrical resistivity of concrete can be measured using different techniques; therefore, the reporting of the type of measurement (e.g. surface, bulk, embedded sensor) and the details of the measurement technique (and corresponding standards, if applicable) is necessary for the interpretation of results. For surface measurements, it is important to describe the probe geometry (four-point vs. two-point electrode,

electrode spacing, etc.) [65-68] and, if applicable, the location and orientation of the probe with respect to the reinforcement [69, 70]. Since moisture state of the concrete surface could affect these measurements, it is recommended to report how the surface is conditioned before the measurements and the moisture state of the surface during the measurements. In the case of the two-electrode setup, it is recommended to report on the measured or assumed cell constant, the presence of any mechanisms that would affect it (i.e., moisture gradients, leaching, and/or carbonation), and any form of verification testing. If concrete resistivity measurements are carried out at a constant AC frequency (as opposed to AC impedance spectroscopy), reporting on the amplitude and frequency of the AC signal is important as these parameters can influence the obtained result [71, 72]. Finally, it is recommended to clearly describe the materials and methods used to establish electrolytic contact to the concrete.

2.5 Exposure conditions

Variations in temperature can have significant effects on the rate of oxidation and reduction reactions and ionic mobility in the electrolyte [60, 73, 74]. Moreover, ambient relative humidity, and in the case of field samples, precipitation or splash water can influence the degree of capillary saturation, which can also affect the rate of reaction and transport properties of the porous system [60, 75, 76]. It is, thus, recommended that information pertaining to the environmental conditions in laboratory or field experiments are reported, especially their variations over time.

2.6 Autopsy information

In addition to corrosion monitoring performed during the testing phase of an experimental program, visual inspection of the cementitious system and embedded steel specimens is crucial to perform at the end of the testing phase. Reporting of important observations in the forms of schematic drawings or photographs is recommended. Visual inspection may provide additional information to interpret the observed results during the testing phase. The following items are of particular importance when conducting a visual inspection.

2.6.1 Cracks in cementitious specimens

Cracks can provide easier ingress of chlorides, oxygen, and moisture and may affect the corrosion behavior [23, 77-80]. Thus, reporting of the location and width of transverse (perpendicular to rebar) and longitudinal (parallel to rebar [81]) cracks on the specimens is necessary. Cracks observed during the autopsy stage of experimental program should be taken into account for the statistical analysis of results since results obtained from cracked specimens can be significantly different from the rest of the specimens. These cracks need to be differentiated from possible cracking that might be introduced during the autopsy procedure.

2.6.2 Type and extent of corrosion on rebar

Reporting on the area of corrosion products as a percentage of the total exposed area of rebar, and whether the corrosion products are uniformly distributed or localized in the form of

pits, is crucial during visual inspection. This may require removing the corrosion products, e.g. by pickling [82] (Fig. 3d). Electrochemical methods used to monitor corrosion current often assume that the total exposed rebar area is corroding, and this assumption leads to errors in case of localized corrosion. It has been suggested that these errors can be minimized by reporting the visually identified corrosion area (apparent anodic zone) that is used in calculations [83].

2.6.3 Location of corrosion on rebar

It is also important to note the location of observed corrosion products relative to rebar and cementitious specimen geometry. It is particularly important to document whether or not corrosion had occurred at parts of rebar not intended as the exposed anode of the test setup (e.g. rebar ends).

It is recommended to note if the observed corrosion has occurred at any particular area of the steel-concrete interface [31]. This may include the moisture state of the corroding areas, concrete cracks, or macroscopic voids such as bleed water zones or air voids. Regarding "corrosion at air voids", it is recommended to accurately describe if corrosion occurred on the part of the metal surface exposed in the concrete void, or if it occurred on the metal surface directly adjacent to the void (but where metal and cement paste are in contact). General literature documenting the influence of air voids on corrosion initiation typically lack this information which hampers elucidating the mechanism of corrosion initiation.

2.6.4 Type and color of corrosion products

The color of observed corrosion products on the steel surface and in the adjacent sections of cementitious system may be different depending on the environmental conditions. Recording of the observed color of corrosion products immediately after exposing of steel (before they react with oxygen) may help interpretation of the observed corrosion mechanism. Based on the environment and availability of oxygen different corrosion product colors were observed for black bars, including orange/red, green, and black [84-87]. Corrosion resistant bars with different chemistries may also exhibit different corrosion products with different colors [88]. Depending on the objectives of the study, the compositional characteristics of the corrosion products might also be useful. In these cases, it is recommended that compositional data obtained from characterization techniques such as XRD and Raman Spectroscopy are also provided.

3 Experimental details to be considered in specific corrosion in concrete studies

3.1 Studies on carbonation

3.1.1 Carbonation method and exposure conditions during corrosion test

The investigation of corrosion due to carbonation is typically performed in accelerated carbonation chambers due to long duration of ambient exposure tests [36]. Because there are no standardized testing protocols for accelerated carbonation testing, a detailed description of the testing method is necessary. In particular, the intended exposure regime (i.e., CO₂ concentration, relative humidity, and temperature)

needs to be specified. Since very high CO₂ concentrations generally do not reflect field conditions, these conditions may unrealistically alter the chemical composition of the specimens [36]. Any special setup that is designed to control environmental conditions within the chamber should be reported. Actual CO₂ concentration, relative humidity, and temperature in the chamber should be monitored and reported for the test duration with adequate temporal resolution so that any deviations from the intended exposure regime are identified.

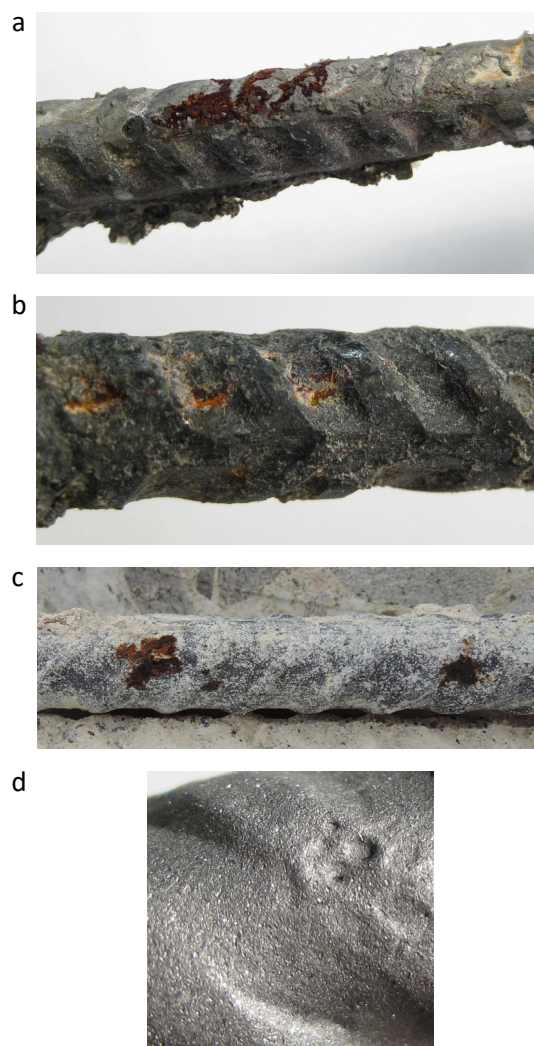


Figure 4. Example of corrosion products autopsy: (a) red-brown corrosion product, (b) corrosion products between the ribs, (c) red-brown corrosion product (Left), black corrosion product (right), (d) corrosion pits on rebar ribs, visible after removal of corrosion products by sandblasting. (Courtesy of U. Angst)

3.1.2 Carbonation depth measurements

Appropriate reporting on carbonation-induced corrosion includes how (e.g. with which indicator, thermogravimetric analysis, etc.) and when the carbonation depth is characterized and the level of carbonation quantified. The number of measurements and statistical variability of the results are necessary for interpretation of results.

3.2 Studies on chlorides

Experiments involving chloride ingress through concrete cover to initiate corrosion involve several critical details.

3.2.1 Exposure solution composition

Because the cation type (e.g., sodium, calcium, potassium, magnesium) has a direct influence on binding properties of concrete and can affect the alkali content of the pore solution [36, 89-92], reporting of the cation type along with the concentration and the pH of the exposure solution is needed.

3.2.2 Chloride introduction method

Introduction of chlorides might involve continuous ponding, wetting/drying cycles, electrical migration under applied voltage, or even admixed chlorides. While the ingress of chlorides is fastest under applied electrical voltage, it is well established that application of an external voltage can affect the chemical composition of the concrete matrix (and pore solution), as well as the corrosion mechanism of reinforcement [56]. When this approach is used, the details of the setup (position and type of counter electrode, etc.), the applied potential, and its duration need to be clearly reported. It is of particular importance to report if the working electrode was polarized.

When chlorides are introduced through wetting/drying, the sequence and duration of each cycle and the total number of cycles must be reported, in addition to the temperature and relative humidity of the environment for the entire duration of exposure. In both approaches, the concentration of the exposure solution would change over time (e.g. due to evaporation); therefore, the appropriate reporting provides details on the precautions to keep the exposure solution concentration stable.

3.2.3 Chloride measurement method details

Chloride measurements often follow a standard testing protocol for the intended chloride type (e.g., acid soluble, water soluble, etc.). The standard (and any deviations from it), or a thorough description of the protocol should be reported. The number of specimens tested to create chloride profiles and statistical variability of the results are necessary for interpretation of results. Moreover, it is also necessary to provide details of the sampling locations, the size of specimens, and the sampling procedure (e.g., wet or dry coring).

3.3 Studies on cracked concrete

Because concrete in service contains cracks, there is increased research on the effect of cracks on rebar corrosion [93, 94]. It is important that works on this subject report the following details.

Source of cracks:

- Shrinkage cracks and the conditions in which they formed [95]
- Structural (loading cracks) and the method of inducing the crack(s) (e.g. three-point bending) as well as details about fixing the crack width (e.g. constantly applied load vs. unloaded systems after cracking, vs. fixed crack opening; in dynamic loading, it may be important to also report

details about time-dependent changes in crack geometry (e.g. crack width and depth evolution)

- Synthetic cracks, produced by placing a shim in the form and casting the concrete around it, then removing the shim, as described in ASTM A955 [12]
- Corrosion-induced cracks
- Cracks from other mechanisms, e.g. alkali-aggregate reactions.

Direction, location and spacing of cracks:

- Transverse or longitudinal to the bar [96, 97]
- Single, branched or numerous as, for example, in the case chemical attack such as sulphate attack or alkali-aggregate reaction
- Spacing between cracks

Geometry of crack:

- Crack width at the concrete surface [98, 99]
- In cases of more than one crack: the crack spacing (crack frequency)
- Whether the cracks circumvent the aggregates or extend through them [100-102]

3.4 Studies in simulated pore solutions

3.4.1 Electrode setup

Studies in simulated pore solutions are typically performed in three-electrode electrochemical cells. Similar considerations to those identified in Sections 2.1.1, 2.1.2, 2.1.3 and 2.4 are also valid for these experiments. However, simulated pore solution tests also have other considerations. Most electrochemical cells use standard sample holders to study disk-type flat surface steel specimens. Cross sections from reinforcing bars can be prepared to fit to these sample holders; however, these would not represent the actual rebar surface conditions, but can only be used to study the effect of the metallurgical characteristics of the exposed metal on corrosion. Alternatively, actual cylindrical surface of the rebar could be used as the working electrode.

3.4.2 Electrolyte composition

For studies in simulated pore solution tests it is crucial to report details of the electrolyte [103, 104]. These include the measured concentrations of the ionic and gaseous species, pH, and conductivity of the solution, the method of measurement (e.g., inductively coupled plasma, ion chromatography, titration etc.). Additionally, it is important to report experimental details that may lead to changes in concentrations and to report measures taken against this. This includes using buffered solutions, details about stirring conditions, exposure to air, and the volume of the solution in the setup. These influencing factors are known to affect the oxygen concentration at the electrode surface and the pH (carbonation of solutions exposed to air), which in turn can affect the results of corrosion tests.

3.5 Other studies

There are other specialized studies on steel corrosion in concrete that are not discussed in this paper. These include studies in the presence of stray currents, corrosion-inhibiting admixtures, cathodic protection, and other electrochemical

protection techniques. Most recommendations provided in this paper are still applicable in these studies; however, they will also contain specialized and custom designed test setups, materials, and testing protocols. The details of all possible cases cannot be covered in this paper; however, as a general rule, all data that are relevant to the analysis and interpretation of corrosion performance can be based on recommendations provided in this paper.

4 Summary and Conclusions

For the reasons given in this paper, the authors recommend the aspects summarized in Table 1 be carefully considered when designing corrosion experiments and reporting the experimental data in studies related to corrosion of steel in cementitious systems. Table 1 may serve as a checklist for authors when preparing reports as well as for reviewers when assessing scientific manuscripts.

Table 1. Checklist of critical considerations in the design of corrosion experiments in cementitious materials to be documented in scientific reports and publications.

Experimental parameter	Recommended to be considered in experimental design and to be reported in publications	Additional recommendations can be found in
Metal	<ul style="list-style-type: none"> - Classification according to standards and processing (e.g. tempcore, coldworked, etc.) - Metal surface condition (as-received, polished, sandblasted, etc.) - Exposed metal surface area - Description of measures taken to avoid rebar end effects (crevice corrosion, etc.) 	Section 2.1
Concrete/mortar/cement paste	<ul style="list-style-type: none"> - Mixture design (w/b ratio, cement content, SCM content, aggregate content, chemical admixtures, etc.) - Material properties (cement and SCM type, composition, and physical properties; aggregate details, etc.) - Concrete casting direction with respect to rebar orientation - Workability, consolidation techniques, finishing techniques, forming materials and surface defects - Curing conditions - Porosity, pore structure information, where available 	Section 2.2
Specimen design and test setup	<ul style="list-style-type: none"> - Number of replicate specimens - Diagram of specimen geometry, ideally including electrode and exposure setups 	Section 2.3
Electrochemical and electrical measurements	<ul style="list-style-type: none"> - Electrodes and electrode setup - For potentiodynamic / galvanodynamic scans: sweep rates, potential or current scan limits, and details about IR corrections - For EIS: voltage amplitude, frequency range, and the number of measurements per decade - For macro-cell currents: zero resistance ammeter or shunt resistor and its value and anode-cathode separation. - For concrete resistivity: surface or bulk measurement; voltage amplitude and frequency; electrode geometry; location of measurement (and method of establishing electrolytic contact to concrete) 	Section 2.4
Exposure conditions (over time)	<ul style="list-style-type: none"> - Temperature - Relative humidity, precipitation, splash water - Immersion / ponding; wet/dry cycle details 	Section 2.5
Autopsy information	<ul style="list-style-type: none"> - Cracks in cementitious specimens - Type and dimensions of corrosion on rebar - Location of corrosion on rebar with respect to any artefact at the concrete interface and including information on whether or not crevice corrosion was observed) - Color of corrosion products 	Section 2.6
Studies on Carbonation	<ul style="list-style-type: none"> - Exposure conditions during carbonation and during the corrosion tests (CO₂ concentration, relative humidity or wetting conditions, temperature) 	Section 3.1
Studies on chlorides	<ul style="list-style-type: none"> - Exposure solution composition - Chloride introduction method - Chloride measurement methods 	Section 3.2
Studies on cracked concrete	<ul style="list-style-type: none"> - Source of cracks - Direction, location spacing of cracks - Crack geometry 	Section 3.3
Studies in simulated pore solutions	<ul style="list-style-type: none"> - Specimen geometry – ribbed surface or cross section Sample holder/specimen details - Solution volume and position of electrodes - Electrolyte composition and measures taken to maintain it (buffering, stirring, shielding, etc.) 	Section 3.4

As a final comment, the authors are aware that the full detailed reporting of all this relevant information may lead to rather long description of experiments, which may cause problems with respect to word-count limitations, especially in scientific, peer-reviewed journals. However, these journals are increasingly accepting the publication of additional electronic supplementary information, which offers an ideal solution to provide all needed experimental information, which is a practice that is increasingly required by funding agencies.

Acknowledgements

The authors of this paper are members of the Corrosion of Metals Committee (222) of the American Concrete Institute (ACI), and/or TC 262-SCI "Characteristics of the steel/concrete interface and their effect on initiation of chloride-induced reinforcement corrosion" of the International Union of Laboratories and Experts in Construction Materials, Systems and Structures (RILEM). Authors acknowledge the logistical support provided by both organizations during the preparation of this manuscript.

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