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1 **Beyond the chloride threshold concept for predicting corrosion of**
2 **steel in concrete**

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10

11 **Abstract**

12 All existing models to forecast the corrosion performance of reinforced concrete structures exposed to chloride
13 environments are based on one common theoretical concept, namely a chloride threshold, as a sharply defined
14 trigger for corrosion, followed by a period of active corrosion. We critically review the resulting treatment of
15 corrosion initiation and propagation as two distinct, successive stages. We conclude that this concept presents a
16 major barrier for developing reliable corrosion forecast models, and that a new approach is needed. In reality,
17 steel corrosion in concrete is a continuous process that is rarely separable into uncoupled, sequential phases. We
18 propose that the focus be placed on the quantification of the time- and space-variant corrosion rate from the
19 moment steel is placed in concrete until it reaches the end of the service life. To achieve this, a multi-scale and
20 multi-disciplinary approach is required to combine the scientific and practical contributions from material science,
21 corrosion science, cement/concrete research, and structural engineering.

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22 **Introduction**

23 Concrete is the most widely manufactured material in the world by mass, and is responsible for about 6-10% of
 24 the total anthropogenic greenhouse gases¹. The use of reinforced concrete will increase substantially in the coming
 25 decades in order to satisfy the demands for the renewal and expansion of our built environment², thereby
 26 dramatically intensifying the burden on the environment¹. Although modern, low-emission cementitious materials
 27 offer opportunities to mitigate the increase in greenhouse gas emissions¹, long-term durability of reinforced
 28 concrete structures remains key to achieving a sustainable infrastructure (**Figure 1a**). In the context of the
 29 worldwide need to save natural and financial resources, it is more important than ever to extend the service life of
 30 ageing structures while assuring their safety². To this end, combined service life predictions and life cycle analyses
 31 (LCA) play an important role in assessing the total environmental impact of novel materials and in tackling the
 32 challenge of ageing infrastructure^{3,4}. In the absence of long-term experience with new low-emission cementitious
 33 materials, service life predictions and LCA would benefit from integrating science-based models to describe the
 34 exposure-dependent degradation and ageing of the materials. Such science-based models are also needed by
 35 owners of reinforced concrete structures and engineers who design and manage them, to know when, and to what
 36 extent, their structures will be deteriorating.

37 Among the various degradation mechanisms of reinforced concrete structures, chloride-induced corrosion of the
 38 embedded steel is by far the most common and costly one⁵. The corrosion-related damage can lead to any
 39 combination of different engineering limit states including reduction of steel cross section, loss of bond between
 40 steel and concrete, and concrete cover cracking/delamination from expansive corrosion products, all of which
 41 threaten the safety and serviceability of structures. Predictive models are needed to provide information on the
 42 time and probability to reach a given engineering limit state⁶⁻⁸.

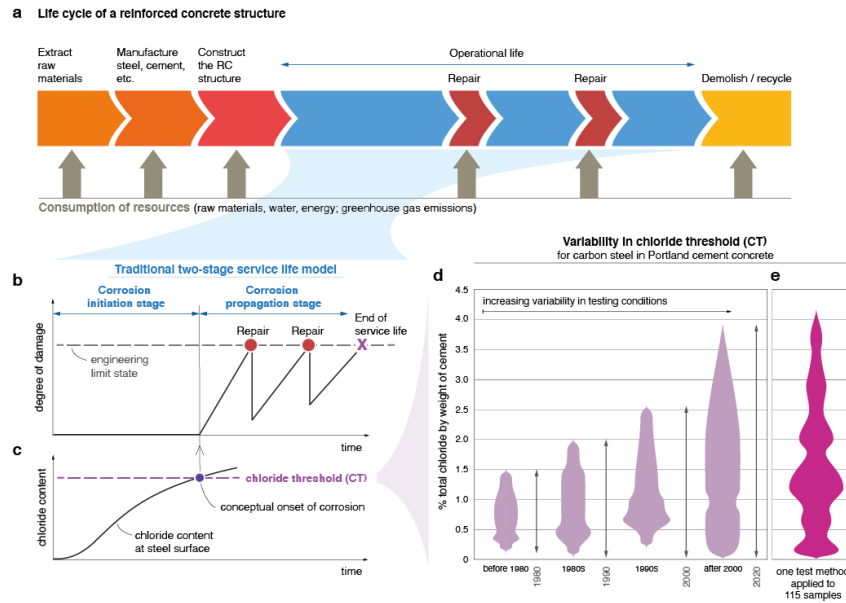


Fig. 1: Elements of the established approach of forecasting the life of a reinforced concrete structure. **a**, life cycle of a structure, showing the steps that most consume natural and financial resources and impact the environment through greenhouse gas emissions. **b**, schematic illustration of the traditional two-stage service life model to predict the operational life of a structure. **c**, conceptual approach at the basis of current models to forecast onset of corrosion, relying on corrosion threshold (CT). **d**, variability in CT reported in the literature over time (based on Refs.²⁰⁻²²). **e**, variability from applying one CT test method to 88 samples taken from engineering structures and 27 samples made in the laboratory (based on the open access data base²⁵). In figures **d** and **e**, the width of the shaded areas indicates the normalized frequency of occurrence of the different values in the reviewed literature, and all data considered are for carbon steel in Portland cement concrete.

43 Steel corrosion in concrete has been studied extensively in the past three decades. In the most recent decade alone,
44 over 5,000 scientific articles have been published on the subject⁹. Many journal publications, books, and
45 committee documents provide comprehensive reviews on the state-of-the-art and the latest progress made on the
46 topic¹⁰⁻²⁴. These reviews clearly indicate that the concept of the so-called “chloride threshold (CT)”, also referred
47 to as “critical chloride content”, is at the core of a vast number of these investigations, particularly those that focus
48 on modeling chloride transport and chloride binding processes²⁵⁻³⁵, corrosion propagation^{10, 18, 23, 24, 36-41}, and
49 corrosion-induced damage⁴²⁻⁵¹. Therefore, it is not the objective of this paper to provide another general review
50 on the subject. Instead, this paper critically focuses on the concept of a chloride threshold.

51 All current predictive models for chloride-induced corrosion of reinforced concrete structures rely on the notion
52 of two distinct and successive stages, initiation and propagation (**Figure 1b,c**). The CT conceptually indicates the
53 level of chloride in the concrete adjacent to the steel that initiates active corrosion, i.e., the start of the propagation
54 stage, as opposed to negligibly slow iron dissolution that occurs when the steel is in passive state. As per Tuutti’s⁵²
55 definition, the initiation stage describes the period in which the aggressive chlorides penetrate the concrete cover,
56 and the subsequent propagation stage is the period in which active corrosion occurs. The concept of CT is therefore
57 closely tied to Tuutti’s definition of service life.

58 While CT may originally have been hypothesized as a pragmatic engineering concept for the decoupled initiation-
59 propagation modelling approach^{53, 54}, it has increasingly become a ubiquitously-accepted parameter that
60 dominates research and practice, with little attention to its scientific validity or practical applicability. Today, the
61 concept of CT is deeply rooted in both engineering and scientific communities, where it is generally considered
62 as “established wisdom” that is rarely questioned. It also serves as an *a priori* concept for research proposals,
63 publications, and international committee work.

64 It is the aim of this contribution to critically assess the decoupled initiation-propagation modelling approach and
65 the CT concept which is needed for its implementation. We address the question of to what extent, and under
66 which circumstances, the CT concept, as presently used, is an adequate tool for predictive modelling of chloride-
67 induced corrosion in structures under design or in-service. Alternative approaches to the formulation of the
68 transition from passive to active corrosion behaviour are considered. It is proposed that an integration of the
69 initiation and propagation stages of corrosion in predictive modelling is necessary, and research areas meriting
70 intensified effort to accomplish this are identified.

71 Background and historical review of CT

72 The pH of the liquid contained in the pore system of concrete is typically above 12.5 and, more commonly, greater
73 than 13 due to the buffering effect of portlandite and the presence of alkali metal hydroxides^{55, 56}. It is well known
74 that carbon steel in such an alkaline medium is passivated⁵⁷, and exhibits negligibly low corrosion rates, less than
75 0.1–1 $\mu\text{m}/\text{y}$ (corresponding to a corrosion current density of $\sim 0.01 - 0.1 \mu\text{A}/\text{cm}^2$)^{13, 58}. In atmospherically exposed,
76 thus aerated, concrete structures, passivity is often associated with relatively noble electrochemical potentials of
77 the carbon steel, in the range of -100 to $+200$ mV vs. the saturated calomel electrode (SCE)^{13, 59}. The passive
78 behaviour of carbon steel in alkaline environments has enabled it to be used successfully as embedded
79 reinforcement in concrete, an ideal application that complemented the unprecedented advancements that humanity
80 experienced since the industrial revolution.

81 By the middle of the last century, it became evident, however, that loss of passivity with consequent active
82 corrosion did occur in many situations associated with the presence of chloride-containing salts (e.g., from
83 seawater, de-icing chemicals, or chemical admixtures)^{53, 54, 60}. Early studies suggested that the chloride content
84 needs to exceed a threshold to initiate corrosion, although it was apparent that there is stochastic variability in this
85 threshold. For steel in an aqueous electrolyte, this threshold appeared to be around a chloride-to-hydroxyl ion ratio
86 ($[\text{Cl}^-]/[\text{OH}^-]$) ranging from 0.5 to 1.0⁵³ but, in later reports, often simply cited as a value of 0.6. For steel embedded
87 in a cementitious matrix, the early studies suggested threshold chloride contents in concrete around 0.4% total
88 chloride by cement mass^{54, 61}. The choice of expressing CT as a $[\text{Cl}^-]/[\text{OH}^-]$, or as a chloride/cement mass (the
89 main source of OH^-) ratio, effectively assumed that the onset of active corrosion in concrete could be viewed
90 primarily as the outcome of a competitive process between aggressive and inhibiting ions. Thus, such CT
91 expressions would be normalized indices that permitted treating a variety of cases – such as concretes with
92 different cement contents – via a single CT value.

93 CT variability as a fundamental problem of the CT concept

94 Despite that definitional normalization, the CT values reported in the literature for carbon steel reinforcement in
95 concrete have shown great variability⁶²⁻⁶⁵, ranging over more than two orders of magnitude. Sources of variability
96 may be broadly divided into (i) physicochemical factors that exist in addition to the relative amount of chloride
97 and hydroxyl ions, (ii) choice of experimental methodology used to determine CT¹⁹, and (iii) inherent stochastic
98 processes in passivity breakdown and pitting corrosion progression phenomena²¹. These factors are addressed in
99 detail in the next section but suffice it to note here that when reinforcing steel is embedded in concrete, the
100 markedly increased degree of heterogeneity at the steel surface amplifies the stochastic behaviour^{20,66}. It is, thus,
101 not surprising that, as the volume of research has increased with time, the range of reported values of CT as
102 defined above increased as well. For example, **Figure 1d** shows the reported range (i.e., scatter) of CT for plain
103 carbon reinforcing steel in a matrix made of Portland cement binder, which is the most traditional, and perhaps
104 the simplest, reinforced concrete system. In the 1970s the state-of-the-art knowledge suggested that active
105 corrosion would start above chloride contents ranging from 0.1 to 1.5 % total chloride by cement weight. By the
106 2000s the range had more than doubled. Recent work showed that CT variability could not be significantly reduced
107 by eliminating some of the variability related to experimental methodology, as is apparent from **Figure 1e**. These
108 data were collected⁶⁷ by rigorously applying one single test method to more than 100 samples of carbon steel in
109 Portland cement concrete from a group of structures. The results still spanned a range comparable to the range of
110 CT reported in the numerous different studies reviewed in⁶²⁻⁶⁴.

111 The variability in CT values, as they are defined and measured, poses a difficult obstacle to developing reliable
112 corrosion performance forecasts for existing, as well as newly designed, structures. One solution would be to view
113 CT as a conservative statistical limit. Choosing a reliability-targeted lower bound for CT based on the complete
114 state-of-the-art data shown in **Figures 1d and e**, however, could lead to the adoption of very low CT values that
115 are generally perceived as unrealistically conservative and in disagreement with anecdotal engineering experience.
116 Furthermore, overly conservative lower bounds inhibit sustainable design, because the conservative approach
117 increases the consumption of resources, caused by the need for greater cover depths, cement contents in the
118 concrete, etc.

119 An alternative approach is to treat the problem stochastically, e.g., by means of probabilistic modeling⁶. However,
120 in such models, the large variability in CT (**Figure 1d**) translates into an even larger uncertainty in terms of
121 estimated service life⁶⁸. Facing this problem, a procedural – somewhat arbitrary – approach has been to narrow
122 the reported range of CT in the literature by excluding selected published CT values. An example is the *fib* model
123 code for service life design⁶ in which CT is based only on one single (laboratory) study⁶⁹. It is difficult to justify
124 why exactly this study is the one to be applied in engineering practice while the majority of the body of knowledge
125 is excluded. If attempts were made to apply rigorous criteria in excluding literature studies, one would inevitably
126 face the conflict of either excluding too much of the literature data (thus making it difficult to justify the harsh
127 selection process) or leaving a scatter of CT data that is still too high for practical engineering purposes.

128 Thus, the CT body of knowledge accumulated over the last decades (**Figure 1d,e**) and applied without
129 qualification offers a poor basis for accurate engineering forecasts. The variability apparent from **Figures 1d and e**
130 hardly allows for an improvement of engineering practice other than, for example, in the comparative
131 examination of the effect of design alternatives. The usefulness of performing further studies measuring CT as a
132 function of different material combinations must then be severely questioned.

133 Factors influencing CT

134 The extensive research carried out over the last decades, has resulted in some of the factors influencing the
135 variability of CT being well understood, while others still need dedicated scientific studies. Mainstream research
136 was generally centered on investigating the effect of material properties of concrete and steel and has shown that
137 the alkalinity of the liquid phase in the concrete pore system^{53, 70}, in particular the local pH buffer capacity at the
138 steel-concrete interface⁵⁵, plays an important role. Another important feature related to the concrete is the range
139 of interfacial macroscopic voids such as entrapped air voids^{71, 72} or bleeding and settlement zones⁷³. Regarding
140 the contribution of the reinforcing steel to the CT variability, it is well documented that surface properties of the
141 steel, including the presence of pre-existing rust layers or mill scale, as well as differences in composition and
142 microstructure, have a significant influence⁷⁴⁻⁷⁹ because they affect the mechanism of chloride-induced corrosion
143 initiation⁸⁰. Numerous studies addressed the influence of concrete mix design, such as the cement type and content
144 and the water/cement ratio^{69, 81, 82}. However, a critical assessment of the relative importance of different factors

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145 for chloride-induced corrosion initiation in concrete, concluded that these concrete-related features have a
146 comparatively small effect²⁰. Instead, that review found that the most dominant parameters affecting initiation of
147 corrosion, besides the metallurgy and surface conditions of the reinforcing steel, were the content and spatial
148 distribution of moisture in interfacial voids in the concrete.

149 This understanding transfers the focus from considering CT as a function of material properties (steel, concrete)
150 towards the actual condition of reinforced concrete in a structure. Here, the moisture condition plays an important
151 role. For instance, changing the moisture condition from 90% relative humidity to capillary saturation was found
152 to affect CT approximately by a factor of 10 (**Figure 2a**)⁸³. Other studies have also highlighted the role of moisture
153 in corrosion of steel in concrete^{84, 85}. Further experimental support for the importance of the moisture state is seen
154 in the findings surrounding the role of interfacial voids in different moisture states. In concrete close to saturation,
155 it was generally found that corrosion tends to initiate adjacent to interfacial voids and that these voids decrease
156 CT^{71, 72, 86}. In concrete below saturation, on the other hand, interfacial voids were very rarely preferential locations
157 for corrosion initiation^{87, 88}. Another aspect related to the moisture condition was that wetting/drying exposure
158 was consistently found to create more favourable conditions for corrosion initiation and to decrease the CT
159 compared to constant moisture states (**Figure 2b**)⁸⁹⁻⁹¹.

160 It should be noted that the effect of the moisture state is not necessarily due to a decrease in steel potential resulting
161 from O₂ starvation at the steel-concrete interface. For instance, the steel potentials prior to corrosion initiation of
162 the experiments shown in **Figure 2b** were very similar for both tested exposure conditions. The pore structure of
163 the concrete will only be completely saturated with water^{92, 93} under extreme long-term immersion. Thus, in the
164 absence of oxygen scavenging processes such as corrosion, sufficient oxygen will generally be present in
165 reinforced concrete prior to corrosion initiation to maintain relatively noble potentials of passive steel in many
166 situations relevant in practice, such as splash water zones in marine and road salt exposure. However, under some
167 conditions, such as long-term submersion, a decrease in oxygen concentration may shift the (passive) steel
168 potential to more cathodic values¹³ with a corresponding increase in the CT^{94, 95} (**Figure 2c**). This phenomenon
169 can play an important role in both corrosion initiation and propagation due to mutual polarization of various zones
170 in the steel assembly⁹⁴.

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171 In addition to the effects of material properties and exposure conditions reviewed above, CT has also been found
 172 to depend on the size of the studied specimen (**Figure 2d**). This size effect, which contributes to the variability
 173 associated with experimental method and stochastic nature of the depassivation process was already recognized
 174 by Evans more than half a century ago⁹⁶. Later, the size effect was quantitatively studied for chloride-induced
 175 corrosion of carbon steel in alkaline solution⁹⁷ and in concrete⁸⁷. It was shown that with increasing specimen size
 176 (e.g., rebar length) under test, both CT and its variability decrease. This can be explained by the circumstance that
 177 chloride-induced corrosion initiation is a localized phenomenon⁹⁸, occurring at the “weakest spot” within the
 178 surface of an exposed metal sample. If experimental CT values are to be used in service life modelling, the size
 179 of the specimens on which CT was determined needs to be considered, because results from small scale laboratory
 180 tests are too optimistic. Another important consequence of the size effect is that the usually small dimensions of
 181 laboratory samples require high numbers of replicate samples to ensure reasonable reproducibility⁸⁷. In common
 182 laboratory testing, this requirement is however rarely satisfied, which may partially explain the large scatter in the
 183 literature.

184 Therefore, all the influencing factors affecting CT – material properties, exposure conditions (moisture,
 185 temperature), potential, and structural aspects (size) – must be considered when applying CT to engineering
 186 practice. Furthermore, it is important to consider the structural consequences of localized corrosion, depending
 187 on the location of corrosion within structural members and possible interferences with other damage⁹⁹. Another
 188 key challenge in translating laboratory data to structures is related to the complexity of the steel-concrete interface
 189 (SCI) and the many local characteristics and heterogeneities present⁶⁶. Due to this complexity, it is virtually
 190 impossible, in laboratory made samples, to create conditions at the SCI that are representative for a given structure.
 191 An important part of the problem is also that the SCI can differ significantly, not only between different structures,
 192 but between different locations within a structure, depending on the age, the conditions during casting,
 193 workmanship, etc.⁶⁶. At the same time, the SCI includes some of the most important influencing factors for CT,
 194 such as the steel surface condition or macroscopic concrete voids. Bearing this in mind, it is difficult to justify
 195 applying CT to conditions that are different from those under which CT was determined. This limited applicability
 196 has severe consequences when attempting to transfer previous understanding from practical experience or

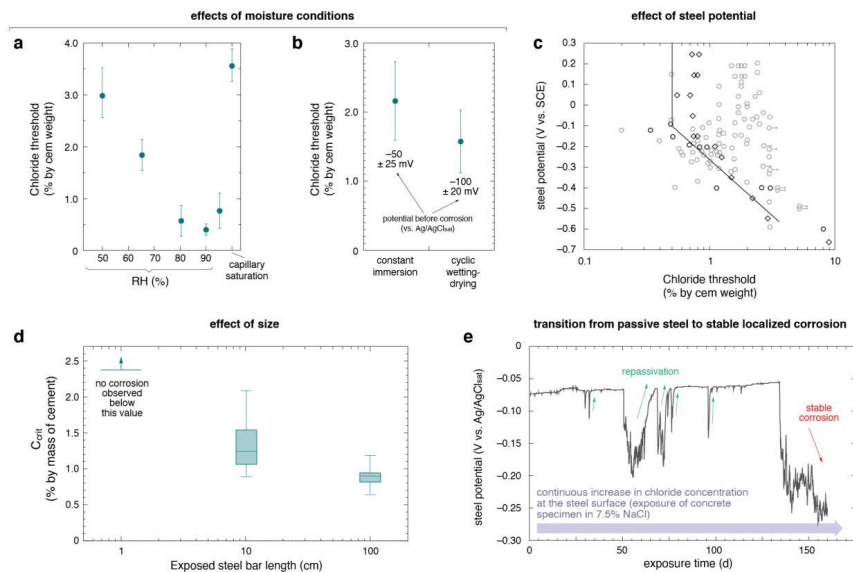


Fig. 2 Influencing factors on CT. a,b, effect of moisture conditions. c, effect of steel potential. d, effect of exposed metal area (size effect). e, effect of criterion for CT illustrated by the fact that the transition from passive steel to active corrosion is a process characterized by depassivation-repassivation events over time during which the chloride concentration at the steel surface increases, until stable localized corrosion is possible. Data replotted from different literature sources, namely for fig. a from Pettersson⁴¹, fig. b from Boschmann⁴⁹, fig. c from Sagüés⁵², fig. d from Angst⁴⁵, fig. e is unpublished data from U.M. Angst.

197 laboratory CT to accurate engineering forecasting questions. For instance, the foregoing arguments seriously
198 challenge attempts to devise test methods¹⁰⁰⁻¹⁰² from which tables could be produced listing CT for different
199 cement types, w/c ratios, steel grades, etc., regardless of the conditions at the SCI and in a structure. Such task
200 may prove to be fruitless.

201 The above describes the inherent shortcomings in establishing meaningful CT values. In the following,
202 corresponding concerns in other aspects of the traditional corrosion initiation-propagation modelling approach are
203 addressed.

204 **The transition from passivity to stable active corrosion**

205 The transition from a passive state to active chloride-induced corrosion is a complex process, and it is well
206 established that this is not an instantaneous and uniform event, but rather a process that occurs over an extended
207 period and at different times for different locations^{103, 104}. Unstable, microscopically small corrosion pits form
208 even at low chloride concentrations; however, these pits can repassivate. This well-known repassivation
209 phenomenon of localized corrosion^{105, 106} can be explained, among other reasons, by mass transport of different
210 ions towards the anodic site and the related competition between Cl^- and OH^- (and other anions) at the anodic
211 surface^{107, 108}. With further increase in chloride concentration, repassivation becomes more difficult until at some
212 point, stable, active corrosion is possible. **Figure 2e** shows an example observed in a reinforced concrete specimen
213 exposed in sodium chloride solution. Repeated repassivation events occurred until finally stable corrosion was
214 observed. It should be noted that considerable time (and related increase in chlorides at the surface) was needed
215 for the transition. It is important to recognize that the early unstable pitting and frequent repassivation phenomena
216 of the sort shown in **Figure 2e** are not related to temporary drying of the concrete. Even under constantly high
217 moisture conditions, repassivation can occur. The moisture and temperature conditions in structures are generally
218 variable over time, which are additional causes for interrupted corrosion propagation. Note that localized pits that
219 repassivate rapidly do not usually generate any harm to a concrete structure. For damage to occur, stable active
220 corrosion must usually develop and occur over an extended time period.

221 In the absence of a clear definition for corrosion initiation, different researchers are likely to interpret the CT value
222 from experiments, such as those shown in **Figure 2e**, differently. In the absence of a definition, even when a
223 standardized testing procedure is developed, it is not likely that CT values that are consistent among different
224 studies can be obtained. A corrosion initiation definition should ideally relate to a measurable parameter and be
225 straightforward to interpret. Since the size of local anode areas cannot be monitored directly, experiments
226 generally involve the monitoring of an electrochemical parameter during chloride exposure. CT is usually
227 determined when the monitored parameter reaches a pre-defined threshold indicating depassivation. However, the
228 transition from passivity to stable pitting occurs over a wide range of chloride concentrations and an indeterminate
229 steel surface area. It is then clear that taking, for instance, the first drop in potential as the indicator will not likely
230 relate it to the chloride concentration at which stable corrosion occurs. Therefore, criteria have been proposed to
231 ensure that the obtained CT relates better to practice by taking into account the repassivation phenomenon, that
232 is, by requiring the potential to stay at a more negative level for a certain minimum time period¹⁰⁰.

233 **Improved approaches to forecasting corrosion of steel in concrete**

234 The concept of CT, resulting in a separation of the service life into two distinct and successive stages (**Figure 1**),
235 caused most of the research to be focused on the corrosion initiation stage. This led to significant advances,
236 primarily in measuring and modelling chloride ingress³² and chloride binding in concrete³⁵. Additionally,
237 substantial efforts in search of CT were made over the last decades, with, as has been shown, very questionable
238 success. It appears, however, that the concept of CT has rarely been critically reassessed. In recent years,
239 atomistic/molecular modeling techniques have been used to study passivity and chloride-induced depassivation
240 of iron in alkaline electrolytes to develop fundamental understanding on how chlorides interact with passive film
241 at the molecular level in idealized systems¹⁰⁹⁻¹¹⁴. Although these techniques have the potential to help future
242 development of new corrosion inhibitors and corrosion-resistant steels, they are not very useful or practical in
243 improving forecasts of safety and sustainability of reinforced concrete structures experiencing corrosion. Machine
244 learning is a field that has received increased attention from researchers studying steel corrosion in concrete and
245 has been shown to be a promising approach for predicting damage in reinforced concrete structures experiencing
246 corrosion^{51, 115, 116}. Some studies even have used machine learning to predict CT or corrosion initiation in concrete
247 structures^{117, 118}. However, these machine learning approaches rely on existing collected data on CT that are still

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248 subject to the challenges associated with the CT concept and cannot address the big questions that are described
249 in this paper. In light of these obstacles, we suggest that the focus be shifted towards approaches that embrace the
250 importance of additional aspects of forecasting safety and sustainability of concrete structures experiencing
251 reinforcement corrosion. This proposed paradigm shift starts with the recognition that initiation and stabilization
252 of active localized corrosion is a process that may occur over significant time, and that after this, periods with
253 higher and lower, sometimes even negligible corrosion rates may occur. This would necessitate the elimination
254 of the clear distinction between initiation and propagation stages. Instead, steel corrosion in concrete would be
255 considered as a continuous process. **Figure 3** summarizes these different aspects by showing schematic plots for
256 both the instantaneous corrosion rate and the accumulated damage over time.

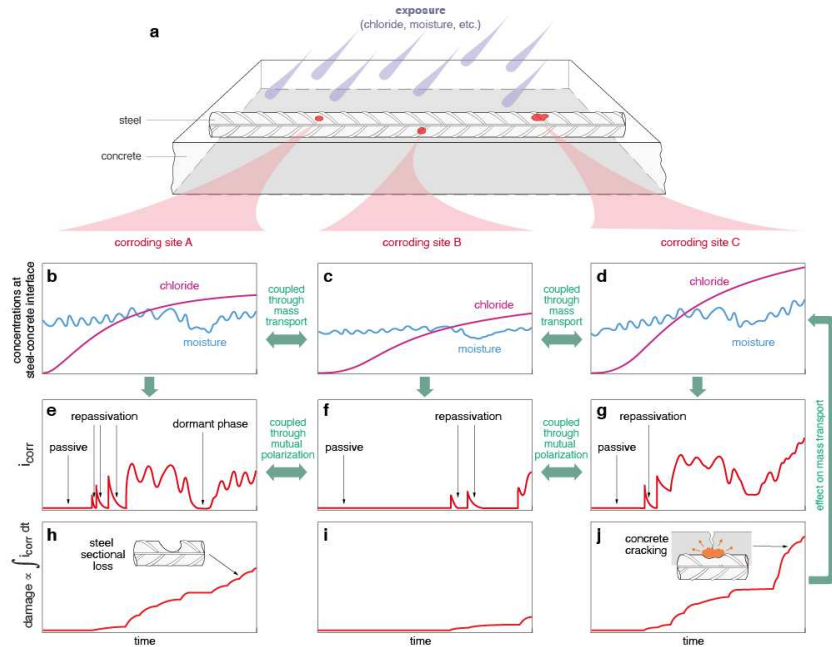
257 It is important to consider that steel experiences significant fluctuations in corrosion rate over time because of the
258 changes in the environmental conditions (e.g., temperature, moisture, chloride exposure) and associated
259 fluctuations in the local microclimate within the concrete. The corrosion rates also vary spatially, i.e., the corrosion
260 rates along the reinforcement surface can show significant variability, particularly in locations of concrete flaws,
261 such as pre-existing cracks. The chloride ingress there will be more rapid and the transition to stable active
262 corrosion may be more abrupt. In some cases, the corrosion rate may decrease after time as the cracks become
263 filled with corrosion products or may heal due to further cement hydration. However, even in sound concrete,
264 some locations remain passive (negligible corrosion rate), while others may exhibit comparatively high corrosion
265 rates in the same time period, for example at intersections of, or bends or welds in, bars. The corrosion behaviour
266 of those different locations are coupled through the mechanism of macro-cell corrosion, which is governed by a
267 number of factors including the supply of aggressive agents (chloride) to the anodic sites, the availability of
268 oxygen at the cathodic sites, the geometry of the corroding system, and the electrical resistivity of the concrete⁹⁴.
269 Due to changes in external environmental conditions, corrosion may cease and dormant phases may occur during
270 the life of a structure. Depending on seasonal variations, such dormant phases may repeatedly occur, e.g., during
271 dry periods. During periods of high corrosion rates, significant steel sectional area may be lost, and significant
272 amounts of ferrous ions may be released into the pore solution adjacent to the steel surface. These species will
273 influence the subsequent dissolution rates and will be subjected to reactive transport processes, and may at some
274 point precipitate in the concrete pore system. The precipitation of corrosion products may first lead to pore
275 clogging (affecting any further transport and corrosion processes), and later lead to macroscopic expansive
276 stresses that may give rise to concrete cracking. The cracks will allow a more rapid transport of species into
277 concrete; therefore, after the first signs of corrosion-induced cracking, decoupling initiation and propagation
278 stages of corrosion is not possible.

279 To take into account all these influences, quantitative, scientific models for localized corrosion are needed that
280 consider the electrochemistry of the steel/porous medium system as well as reactive mass transport, corrosion
281 product precipitation and concrete cracking as well as porosity changes related to these phenomena. Although
282 significant advances have been made in the modelling of steel corrosion (i.e., prediction of corrosion rates) in
283 sound concrete^{36, 37, 119, 120}, there are limited research efforts to systematically incorporate the simultaneous and
284 coupled processes of transport of aggressive species, moisture, and temperature variations in concrete structures,
285 the progression of reinforcement corrosion rates, and deterioration of the concrete. We see major opportunities
286 for scientific advances in combining measurements and modelling of these aspects with recent developments in
287 invasive and non-invasive imaging techniques to characterize the pore structure at the SCI.

288 To reliably quantify corrosion rates for conditions relevant for practice, the time-variable exposure should be
289 considered, as this, together with moisture transport and moisture retention of the concrete cover zone, determines
290 the time periods during which significant active corrosion is possible (**Figure 3**). Local and time-dependent
291 exposure conditions in terms of concrete surface wetting (e.g., splash water, rain), relative humidity, temperature,
292 chloride loading, etc. and material properties such as pH and electrical resistivity are needed for the quantification
293 of corrosion rates¹²¹. For many geographic regions in the world, high quality meteorological data are available to
294 describe the exposure conditions. To link these “macroscopic” exposure data to the *in-situ* microclimate for
295 specific situations, e.g., road splash water on a bridge barrier wall, advantage should be taken of state-of-the-art
296 monitoring systems, possibly supported by machine learning algorithms. Such sensor systems^{122, 123} allow
297 monitoring *in-situ* the ingress of moisture, chlorides, and pH evolution. Collecting temporospatial variations of
298 such microclimatic data within a structure and relating it to macroscopic meteorological exposure data would
299 open new perspectives for better exposure condition modelling and, thus, pave the way towards more reliable
300 modelling of the performance of reinforced concrete structures in their exposure environments.

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302 **Fig. 3:** Illustration of monitored or predicted corrosion rate and related damage accumulation over time. Depending on the
 303 exposure climate and concrete properties, local microclimate at the steel-concrete interface can be different at different locations
 304 in the structure (examples A, B, C; Fig. a-d). As a result, the corrosion evolution – comprising periods of passivity, active corrosion,
 305 and dormant phases – will be different (Fig. e-g). Note that the different corroding sites and their electrochemical behavior are
 306 coupled through possible mutual polarization (depending on various factors, such as concrete electrical resistivity distribution).
 307 Note that the type of damage at the structural level may differ (e.g., steel sectional loss (Fig. h) or concrete cracking (Fig. j))
 308 depending on various parameters such as the pore structure and mechanical properties of the cementitious matrix, iron solubility
 309 and speciation in the given local pore liquid chemistry (pH, chlorides, oxygen, etc.). Precipitation of corrosion products in the
 310 concrete pore system can lead to pore clogging and concrete cracking which both affect the mass transport behavior.
 311

312 Additionally, empirical data of the temporal variations of corrosion rates of steel in concrete should be collected
 313 and correlated to the micro- and macroclimatic conditions as mentioned above. It must be recognized, however,
 314 that state-of-the-art measurement techniques for the instantaneous corrosion rate of reinforced concrete lack the
 315 accuracy to provide reliable data¹²⁴⁻¹²⁷. A particular problem is that present electrochemical corrosion rate
 316 measurement techniques provide data averaged over the measurement area and are unable to focus on the local
 317 corrosion rates. It is clear that future endeavours must focus on improving corrosion rate prediction models and
 318 corrosion rate sensing devices that can accurately work in real structures, to make significant advancements in
 319 service life prediction of reinforced concrete.

320 **Concluding remarks**

321 On the basis of the above discussion, one could ask: is it time to abandon the concept of a CT with its associated,
 322 sharply defined, separation between initiation and propagation stages? As is clear from this review, the answer to
 323 that question is not straightforward. Concerning scientific research, now is definitely the time to shift the focus
 324 from CT to questions on the mechanisms and factors controlling the entire service life of a structure. After more
 325 than half a century of searching for a CT, and with the current limited usefulness of the concept in engineering,
 326 there are clearly research areas that are more promising in terms of achieving understanding and knowledge that,
 327 finally, would allow substantially enhanced predictions of the life of concrete structures.

328

329 - First, the mechanism of the transition from passive to stable active localized corrosion of steel in the complex
330 porous medium (concrete) must be fully established. The onset of active corrosion of steel in concrete is a
331 phenomenon with complexity clearly beyond published pitting and depassivation theories, which are
332 generally developed for the case of a well-defined metal electrode immersed in a homogeneous liquid
333 electrolyte^{128, 129}. We advocate the research community to consider the heterogeneity of the steel, the concrete
334 and the steel-concrete interface more specifically in attempts to study the transition from passive steel to
335 stable localized corrosion of steel in concrete. An example discussed in this review would be the role of
336 interfacial concrete voids, especially the effect of their moisture state and the chemical environment within
337 the voids in the process of corrosion onset. This can only be addressed by combining new advanced material
338 characterization techniques¹³⁰ with holistic theory considering the interdependencies between physical,
339 chemical, and electrochemical principles.

340

341 - Second, to ensure that corrosion predictions are relevant and useful for the engineering community, there is
342 a need to spend more effort on the quantification of corrosion *rate*, in particular the temporospatial variability
343 of corrosion rates in a structure. We see opportunities in methods for the in-situ measurement of corrosion
344 rate as well as in modeling, as outlined below:

345

346 - Reliably measuring the corrosion rate of localized corrosion in concrete structures can be achieved by
347 combining refined electrochemical measurements with numerical models¹³¹⁻¹³⁶, taking advantage of the
348 progress in computational power and mechanistic understanding made over the last decades. In addition to
349 non-destructive techniques for on-site measurements, the potential benefit from monitoring techniques,
350 particularly their ability to create large amounts of time- and space-resolved data, is huge. This further creates
351 opportunities in relating time-variable exposure conditions (e.g., based on meteorological data available for
352 many regions in the world) to the temporospatial microclimates in the concrete (e.g. based on embedded
353 sensors) and to couple these microclimatic variations to corrosion rates. Such approaches involving large
354 data-sets from structures, combined with data science methods, will enhance the understanding of corrosion
355 behaviour of steel in concrete under actual exposure conditions.

356

357 - Scientific models for localized corrosion and related structural deterioration should integrate the
358 electrochemistry of the steel in the cementitious porous matrix and link it to the various relevant transport
359 processes (moisture, heat, ionic species, gases) and related phenomena, namely chemical reactions such as
360 corrosion product precipitation, and their physical consequences (concrete cracking, porosity changes).
361 Additional opportunities for scientific advances in this regard lie in combining modelling and experiment,
362 especially data on the temporospatial microclimate mentioned in the previous point and microstructural
363 characterization of the SCI with recent developments in invasive and non-invasive imaging techniques.

364 These scientific developments will take time to allow for a breakthrough in forecasting corrosion of steel in
365 concrete. Thus, it is yet too early to advocate abandoning the CT concept for engineering purposes, especially in
366 cases where only comparative evaluation of alternatives is sought. However, research must evolve to include how
367 to translate CT to conditions in practice, beyond just expanding the database of CT measurements. That translation
368 to practice concerns aspects related to the moisture and temperature conditions during testing vs. actual exposure
369 conditions of a structure, aspects related to the complex features of the steel-concrete interface (including concrete
370 flaws, particularly macro- and micro-cracks), as well as addressing the conceptual questions raised by the size
371 effect.

372 In summary, to make progress in all the above-listed research priorities, a multi-scale and multi-disciplinary
373 approach is needed to combine the scientific and practical contributions from material science, corrosion science,
374 cement/concrete research, and structural engineering. This would present an opportunity to, at least partially,
375 evolve away from the commonly held view of the service life being separated in two distinct and successive
376 phases, and to consider steel corrosion as a continuous process. Instead of the binary approach of “passive” and
377 “active” steel, the corrosion rate will become a more prominent parameter, both in monitoring and predicting the
378 service life. One major advantage of this approach is that it would reduce or even eliminate the reliance on CT,
379 thus obviating many of the difficulties reviewed here.

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380 Finally, it should be mentioned that one of the challenges associated with the lack of progress made in forecasting
 381 corrosion of steel in concrete, is that engineers are forced to be very conservative to ensure uncritical
 382 concentrations of chloride at the steel level over the design life of a structure. This translates into unnecessarily
 383 high consumption of materials and energy, hence, excessive greenhouse gas emissions and costs. Therefore,
 384 uncritical adherence to the 2-stage model framework and the concept of CT risks compromising the urgent needs
 385 to reduce the environmental impact of the construction sector, and is clearly not in alignment with ambitions such
 386 as the “net zero target” of the Global Cement and Concrete Association¹³⁷, aiming at entirely decarbonizing the
 387 cement and concrete industry within the next 30 years.

388

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405 **Author contributions**

406 The five authors were equally involved in developing the concepts, in editing the manuscript and in collecting
 407 literature. U.M.A. and O.B.I. wrote major parts of the manuscript. U.M.A. designed the figures.

408 **Data availability statement**

409 Most of the data analyzed in this study is accessible in publications according to the indicated references.
 410 Additional data that support the findings of this study are available from the corresponding author upon reasonable
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412

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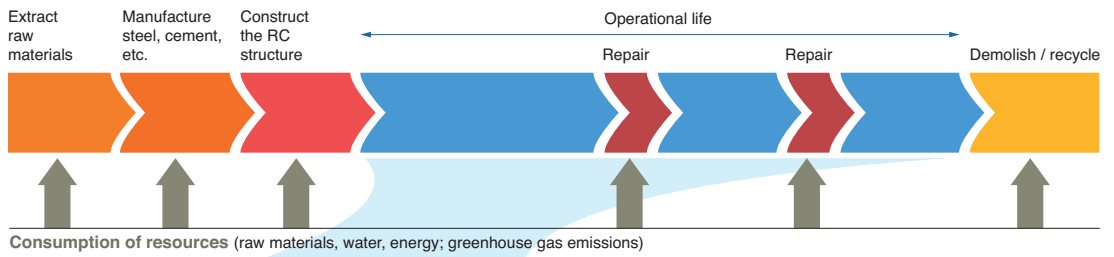
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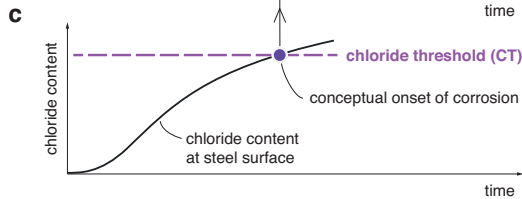
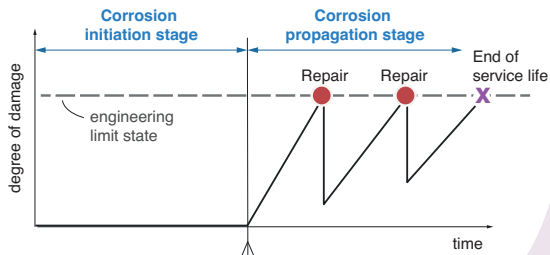
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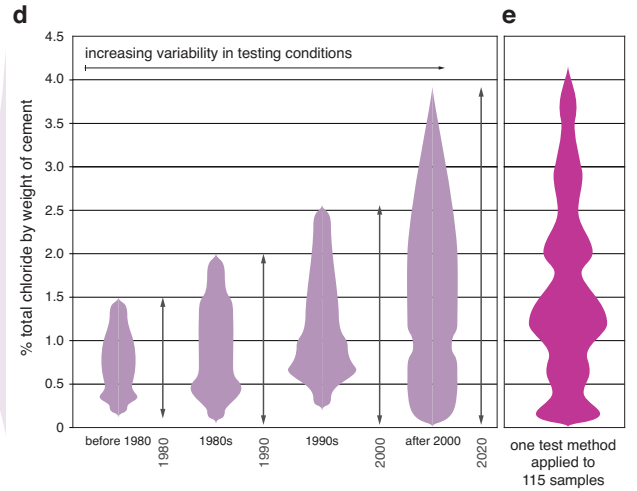
a Life cycle of a reinforced concrete structure



b Traditional two-stage service life model

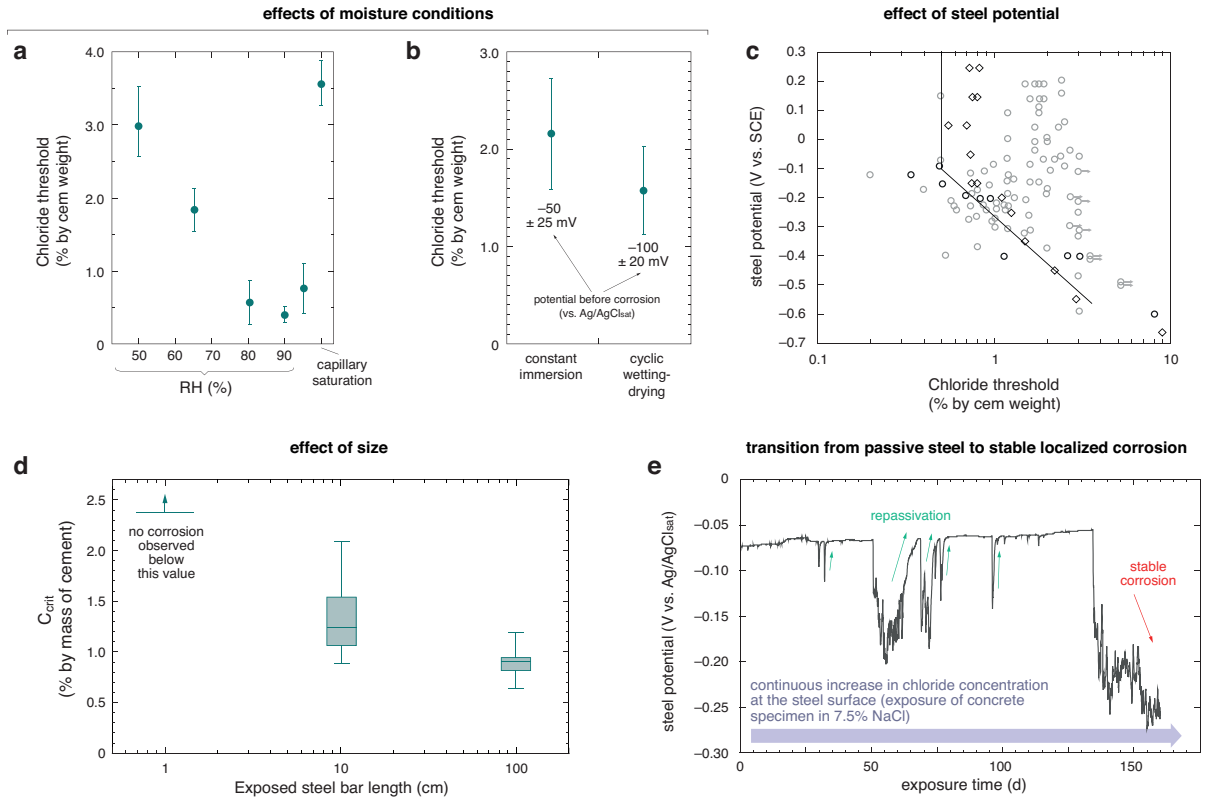


Variability in chloride threshold (CT) for carbon steel in Portland cement concrete



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