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Relationship between concrete resistivity and corrosion rate – A literature review

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ABSTRACT

The process of reinforcement corrosion in concrete is partially controlled by the transport of ions through the concrete microstructure. Ions are charged and the ability of a material to withstand transfer of charge is dependent upon the electrical resistivity. Thus, a connection could be expected between the corrosion process of steel embedded in concrete and the electrical resistivity of concrete. This paper reviews research concerning the relationship between corrosion rate and concrete resistivity. Overall, there exists an inverse proportional correlation between the parameters. However, the dependency varies between studies and one single relationship cannot be established between corrosion rate and resistivity. To address the variation, the article reviews and evaluates the influence of factors including the experimental setup, the concrete mix design and the cause of corrosion.

1. Introduction

Corrosion of steel in concrete has caused numerous costly repairs and a considerable number of structural failures during the last centuries [1]. It is of high interest to evaluate the corrosion process in a sufficient way not only for existing structures but also for the design of new structures. Concrete resistivity is, in this respect, seen as one of the most important parameters that can help to assess corrosion of steel in concrete. Investigations have found correlations between concrete resistivity and both, the initiation and the propagation period [2–22] (Fig. 1).

This paper addresses the relationship between corrosion rate and concrete resistivity (referred to hereafter also as the "C–R relationship"). It is today widely accepted that the corrosion rate decreases with increasing concrete resistivity under common environmental exposure conditions (excluding submerged structures). However, considerable and not fully clarified deviations are found between studies published in the literature.

1.1. Background

The electrical resistivity ρ (Ω m) of a material describes its ability to withstand the transfer of charge. It is the ratio between applied voltage and resulting current multiplied by a cell constant and is thus a geometry independent property [23]. The inverse of resistivity is conductivity σ. The range spanned by resistivity is one of the greatest of any material property. For concrete it varies between 10^6 Ω m for oven dried samples to 10 Ω m for saturated concrete [24]. Electrical resistivity in concrete is ascribed to microstructure properties such as porosity and pore solution characteristics. The degree of saturation of the pore structure has been identified as the most important factor influencing concrete resistivity [11,25,26] and temperature also has a considerable impact [27].

In the highly alkaline environment of the concrete pore solution, steel is protected against corrosion by a thin layer of iron-oxides (passive film). However, this passive film is not stable in the presence of a sufficient amount of chlorides or when the concrete surrounding the steel is carbonated. Corrosion can then occur. The propagation of corrosion of steel embedded in concrete is an electrochemical reaction that consists of four separate processes (Fig. 2). Each step represents a resistance against the flow of current in the cell. The resistances are connected in series and consequently the corrosion current will be limited by the highest resistance. The resistance of current flow through the steel will be low with respect to the other three processes. Accordingly, either the cathodic, anodic or concrete resistance limit the corrosion rate, which depends on environmental and/or material properties [6,13,28,29]. Concrete resistivity can have a direct influence on the corrosion process by describing the flow of current between anode and cathode regions (R_{con} in Fig. 2). However, through its ability to describe the moisture stage and the flow of ions such as chlorides through the concrete microstructure, it can also have an indirect correlation to the corrosion process by influ-

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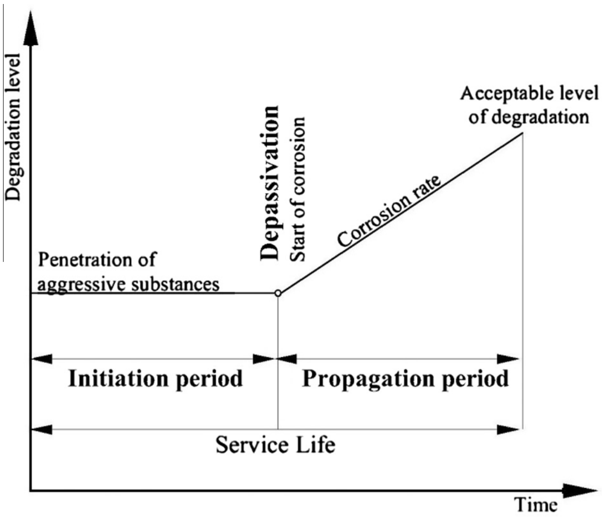

Fig. 1. Definition of the Service Life based on Tuutti's model [22].

encing the anodic and cathodic reaction rates. The corrosion rate is commonly described as current density i_{corr} (μA/cm^2).

Reinforcement corrosion due to carbonation usually occurs over a large area of reinforcement surface. Cathodic and anodic areas are adjacent and a uniform dissolution of the steel takes place. This mechanism is called microcell [28] or uniform [30] corrosion. Uniform corrosion can also appear if the chloride content along the rebar is very high [1]. Generally however, localized pits develop in the presence of chlorides. The anodic area in the localized pit is much smaller with respect to the cathodic area (the passive rebar surface around the pit) and anodic and cathodic regions are separated in space creating a macrocell. Hence, corrosion in the presence of chlorides is referred to as macrocell corrosion [30].

It is widely accepted that concrete resistivity can easily be measured, especially in the field, compared to other parameters in corrosion science such as the corrosion rate [31]. A relationship between concrete resistivity and corrosion rate would consequently allow the assessment of the corrosion stage in an efficient and reasonably priced way. This can be seen as the main reason for the intensive research over the last decades on the C–R relationship. Assessment criteria to quantify corrosion activity by concrete resistivity measurements can be found in the literature (Table 1). However, a high variation between the threshold values is observed. An upper limit of 1000–2000 Ω m can be identified from the comparison over which the corrosion rate will be low. As a lower limit, concrete with a resistivity under 50 Ω m is likely to allow heavy corrosion. On site, resistivity values between 50 and 1000 Ω m are commonly obtained for concrete made of ordinary Portland cement (OPC), up to 6000 Ω m for blended cements [23]. The upper and lower limits are consequently too rough for the detailed assessment of corrosion activity. To address a more detailed description of the C–R relationship, this report reviews and evaluates literature on experimental investigations, compares their results, and identifies differences between them.

Table 1
Criteria for the assessment of corrosion activity in terms of concrete resistivity (see references).

Refs.	Corrosion intensity in terms of resistivity (Ω m)			Corrosion induced by
	High	Moderate	Low	
[2]	<50	50–120	>120	
[3]	<65	65–85	>85	
[9]	<70	70–300	>300–400	Chlorides
[16]	<100	100–300	>300	
[20]	<200	200–1000	>1000	
[11]	<50	Under discussion	100–730	
[12]	<100	100–1000	>1000–2000	
[15]	<100	100–1000		General
[37]	<50	50–200	>200	
[18]	<80	80–120	>120	

1.2. Objective and methodology

The primary objective of this article is to review existing research on the relationship between corrosion rate and concrete resistivity. The report identifies the applicability and limitation of the C–R relationship and evaluates its suitability for the assessment and prediction of the propagation period. Finally, key points are identified for future research in the area.

An extensive literature search was undertaken. The main reference sources were international studies investigating the relationship experimentally. A review was prepared of the most relevant literature. A comparison was made of the experimental setup (Section 2), the way in which the recorded data was analyzed (Section 3) and the results obtained (Section 4). Several parameters influencing the C–R relationship were identified and compared (Fig. 3). The information observed from the literature search was supplemented by two models which are based on the C–R relationship and which are compared to the experimental data (Section 5). Further selected reports containing information on the C–R relationship complement the literature review. Investigations were considered for both chloride and carbonation-induced corrosion.

Within the individual studies, different terminology has been used to describe the relationship. Some authors compared the corrosion rate with the concrete resistivity, while others preferred concrete conductivity. The differences in the terms used affect the analyses of the relationship. A correlation between concrete resistivity and corrosion rate indicates an inverse proportionality, whereas a relationship between concrete conductivity and corrosion rate gives a direct proportionality.

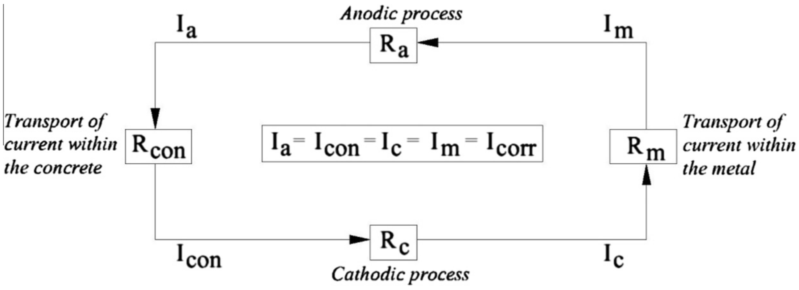

Fig. 2. Electrochemical mechanism of reinforcement corrosion [1].

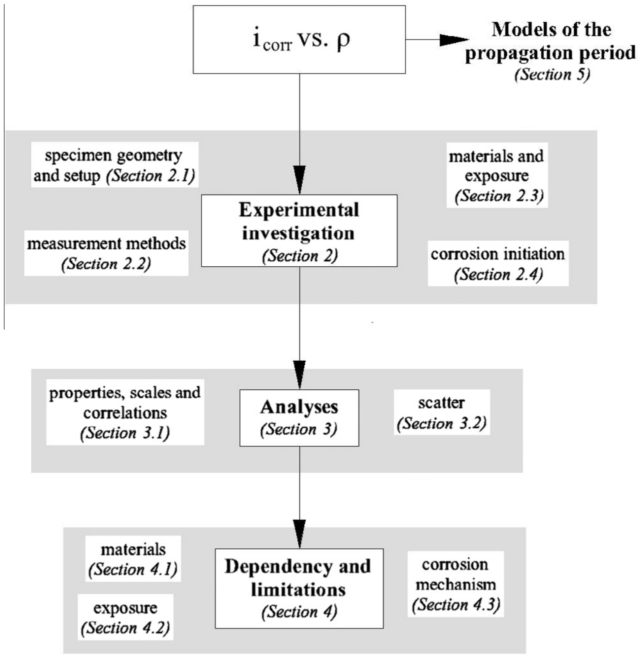

Fig. 3. Outline of the literature review.

Table 2
List of symbols and abbreviations.

	Explanation
C–R relationship	Relationship between corrosion rate and concrete resistivity
Carbo	Corrosion induced by carbonation
Cl	Corrosion induced by chlorides
R	Concrete resistance (Ω)
ρ	Concrete resistivity (Ω m)
σ	Concrete conductivity (1/(Ω m))
i_{corr}	Corrosion rate (μA/cm^2)
R_p	Polarization resistance (Ω)
Log	Logarithmic axis
N	Linear axis
LPR	Linear polarization resistance
WE	Working electrode (corroding steel bar)
CE	Counter electrode
RE	Reference electrode
w/b	Water/binder ratio
$c{:}a{:}w$	Cement:aggregate:water
OPC	Ordinary Portland cement
SC	Slag cement
BFSC	Blast furnace slag cement
FA	Fly ash
/	Not reported

The reviewed data was compared and evaluated in forms of tables and graphs. Tables are ordered by the year of publication. Abbreviations and symbols are defined in Tables 2 and 3. Detailed information on the experimental setups is presented in Tables 4–8. Properties and scales used to analyze the C–R relationship are compared in Table 9. The table includes one additional study besides the ones presented in Tables 4–8. The study contains measurement data from the field [32]. It is the only investigation found in the literature search which is based on field investigations.

The experimental data was fitted to linear trend lines in most reports. The regression lines were compared in the two scales most commonly used in the literature (Figs. 4 and 5). The reproduction of the fitted lines from the references and the transformation between scales was done simply by picking 10 evenly distributed points out of each trend line and connecting them by a straight line. To the extent possible, the regression lines were drawn in the range in which they were found in the reported experiments. The scatter of the observed regression lines is illustrated in Fig. 6. Parts of the reviewed experimental data could not be included in the graphical comparison [7,10]. This data was reported in properties which are dependent on the geometry of the sample and the measurement arrangement. Details on these points were not adequately clarified in the appropriate publications.

2. Comparison of the experimental investigations

Experimental setups to study the C–R relationship must consist of the following:

- Working electrode, preferably construction steel embedded in a mortar or concrete sample to reflect practice-related conditions.
- A technique to measure corrosion rate, either from the surface or as an embedded device.
- A technique to measure concrete resistivity.
- A method to initiate corrosion.

No standardized test method exists to investigate the C–R relationship. Experimental setups were developed individually according to the points listed above and depending on the focus of the work. Most experiments studied not only the C–R relationship but also other corrosion parameters such as electrical potential or chloride diffusion. The following sections compare the experimental setups reported in the literature. The extent to which differences in the setups can influence the C–R relationship will be discussed. A comparison of the experimental setups is given in Tables 4–8.

2.1. Specimen geometry and setup

Commonly, the C–R relationship was studied on samples with dimensions between 10 and 40 cm [4,7,10,13,16] (Table 4). Smaller

Table 3
Explanation to the literature reviewed in Figs. 4 and 5.

Line style	Refs.	w/b	Cement type	Cause of corrosion
————————	[13]	0.45	Slag cement (70%)	Carbo
————————	[5]	0.5	Different	Carbo
- - - - - - - -	[13]	0.45	Slag cement (70%)	Cl
- - - - - - - -	[4]	0.45	Slag cement (25% and 50%)	Cl
— · · — · · — · · —	[20]	0.5	/[a]	Cl
	Samples over 10 years old			
— · — · — · — ·	[6]	0.5	/[a]	Cl
— · — · — · — ·	[9]	0.5	/[a]	Cl
— · — · — · — ·	[16]	0.4/0.6	/[a]	Cl
━ · ━ · ━ · ━ ·	[13]	0.45	OPC	Cl

[a] Assumed OPC.

Table 4
Details of the specimen geometry, in terms of specimen size, reinforcement type and number of specimens used in the investigation of the relationship between corrosion rate and concrete resistivity in the studies included in this review (see references).

Refs.	Specimen size		Reinforcement			Total number of specimens
	Type	Size (mm)	Ø (mm)	Exposed area (cm^2)	Cover depth (mm)	
[4]	Slab	114 × 300 × 400	13	102	56	18
[5]	Cube	20 × 55 × 80	/	6	7	/
[6]	Cube	Length 50	1.5	2.4	/	/
[7]	Cube	180 × 180 × 180	/	2	20	7
[9]	Cube	20 × 55 × 80	/	/	/	/
[10]	Cylinder	Ø 70 × 150	12	/	/	/
[13]	Cube	100 × 100 × 300	6	11.4	10, 30	32
[14]	Slab	1180 × 1180 × 216	16	/	25, 51, 76	40
[16]	Cylinder	Ø 150 × 200	10	40	15	16
[20]	Slab	1330 × 1330 × 70	8	/	/	2

Table 5
Details of the measurement methods used to record corrosion rate and concrete resistivity in the investigation of the relationship between corrosion rate and concrete resistivity in the studies included in this review (see references).

Refs.	Corrosion rate			Concrete resistivity			
	Technique	Details	Correction for ohmic drop	Technique	Embedded (WE)	Embedded (Ref. bars)	From the surface
[4]	LPR	Embedded CE RE on the surface	/	2 – Electrodes	×		
[5]	LPR	From surface	Yes	2 – Electrodes		×	
[6]	LPR	From surface	Yes	2 – Electrodes	×		
[7]	LPR	Embedded device	Yes	4 – Electrodes		×	
[9]	LPR	Embedded CE RE on the surface	/	2 – Electrodes	×		
[10]	LPR	From surface	Yes	Ref. sample 2 – electrodes			×
[13]	LPR	Between 3 embedded rebars	No	2 – Electrodes		×	
[14]	LPR Galvanostatic	From surface From surface	Yes	Measured with the LPR device			
[16]	LPR	/	Yes	2 – Electrodes	×		
[20]	LPR and others	From surface	Yes	/			

Table 6
Details of the materials used in the investigation of the relationship between corrosion rate and concrete resistivity in the studies included in this review (see references).

Refs.	Type	Amount of cement or proportion (*c*:*a*:*w*)	Cement type	*w*/*b*
[4]	Concrete	400 kg/m^3	OPC OPC + 25% slag OPC + 50% slag	0.45
[5]	Mortar	1:3:0.5	OPC sulfate Resistance PC slag cement pozzolanic cement OPC + 30% FA fly ash cement	0.5
[6]	Concrete	1:3:0.5	/	0.5
[7]	Mortar	1:6:0.9/1.1	OPC	0.9, 1.1
[9]	Mortar	1:3:0.5	/	0.5
[10]	Concrete	1:5.85:0.55	OPC OPC + 30% FA	0.55
[13]	Mortar (0–8 mm)	300, 330 kg/m^3	OPC BFSC (70% slag)	0.45, 0.65
[14]	Concrete	337–382 kg/m^3	/	0.41–0.45
[16]	Concrete	300, 400 kg/m^3	/	0.4, 0.6
[20]	Concrete	1:3:0.5	/	0.5

Table 7
Details of the exposure conditions used in the investigation of the relationship between corrosion rate and concrete resistivity in the studies included in this review (see references).

Refs.	Moisture conditions	Temperature	Measurement period
[4]	Changing exposure	Laboratory/105 °C	~1 year
[5]	Changing exposure	Laboratory	500 days
[6]	Wetting/drying cycles	Laboratory	/
[7]	Stored in 38–92% RH changing over time	25 °C	130 days
[9]	Stored in 50% RH	50 °C	500 days
[10]	Immersed in either salt water or tap water	Laboratory	1 year
[13]	Changing exposure	Changing	5 years
[14]	Outdoor exposure	Outside	5 years
[16]	Wetting/drying cycles, seashore	Laboratory, outside	1000 days
[20]	Surface wetting	Laboratory	Several years old specimens 30 days observation

Table 8
Details of the corrosion initiation used in the investigation of the relationship between corrosion rate and concrete resistivity in the studies included in this review (see references).

Refs.	Carbonation	Mixed-in chlorides by cement weight	Wetting/drying cycles
[4]			3.5% NaCl solution
[5]	Accelerated		
[6]		3% $CaCl_2$	
[7]	Accelerated		0.4 or 1% Cl^- solution
[9]		2% NaCl	
[10]		2% Cl^-	5% NaCl solution or pure water
[13]	Accelerated	2% $CaCl_2$	
[14]		0–7.2 kg/m^3 Cl^-	
[16]		0.16–1.65% Cl^-	3.5% Cl^- solution or outside
[20]		3% $CaCl_2$	

Table 9
Details of the analyses and results from the investigation of the relationship between corrosion rate and concrete resistivity in the studies included in this review (see references).

Ref.	Scale	Relation	Dependency	Applicability
[4]	Log (ρ) – Log (i_{corr})	Linear	Not on cement type	/
[5]	Log (R) – Log (i_{corr})	Linear	Not on cement type	Active corrosion
[6]	Log (σ) – Log (R_p)	Linear	/	Active corrosion, RH < 95%
[7]	N (σ) – N (i_{corr})	Linear	/	/
[9]	Log (ρ) – Log (i_{corr})	/	/	/
[10]	Log (R) – Log (i_{corr})	Linear	Cement type	/
[32]	Log (ρ) – Log (i_{corr})	/	/	/
[13]	N (σ) – N (i_{corr})	Linear	Cement type cause of corrosion	Active corrosion
[14]	N (ρ) – N (i_{corr})	Logarithmic	Chloride content, temperature	Active corrosion, not saturated
[16]	Log (ρ) – Log (i_{corr})	Linear	Not on w/c ratio	/
[20]	Log (ρ) – Log (i_{corr})	Linear	/	Active corrosion

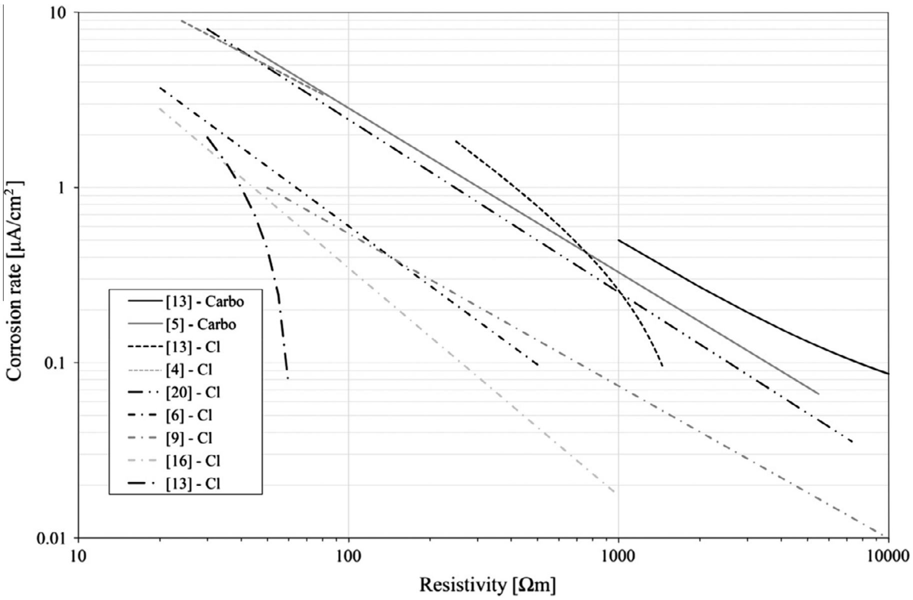

Fig. 4. Comparison of the regression lines for the relationship between corrosion rate and concrete resistivity observed in literature (see references) in the log–log scale, details and abbreviations see Tables 2 and 3.

samples with edge lengths under 10 cm [5,6,9] as well as specimens with dimensions over 1 m [14,20] were more seldom used. The steel diameter varied between 1.5 and 16 mm, according to the sample size. Mostly, no detailed information was provided about the type of the steel embedded, both ribbed and smooth steel was used. In the majority of the studies, several reinforcement bars were placed parallel in cover depths ranging from 7 to 76 mm.

It is seldom discussed to what extent sample size influences experimental investigations of the corrosion process. It seems of minor importance from an electrochemical point of view for localized corrosion, provided that enough cathode area is available [33,34]. For samples with heavily corroding anodes and a comparatively small cathode area, cathodic control might be in force and limit the corrosion rate. No information about the size of the anode and the ratio between anode and cathode is given in the reviewed

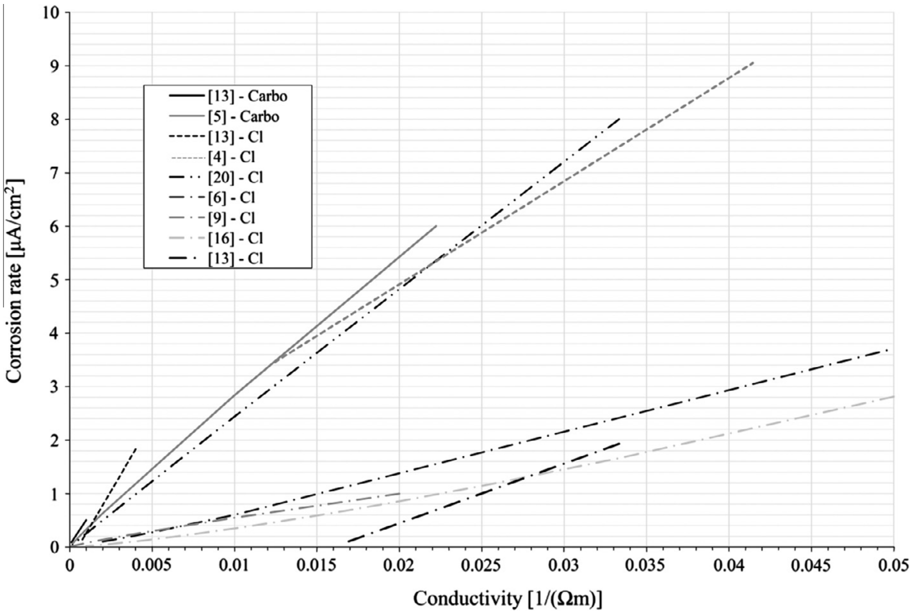

Fig. 5. Comparison of the regression lines for the relationship between corrosion rate and concrete conductivity observed in literature (see references) in the linear–linear scale, details and abbreviations see Tables 2 and 3.

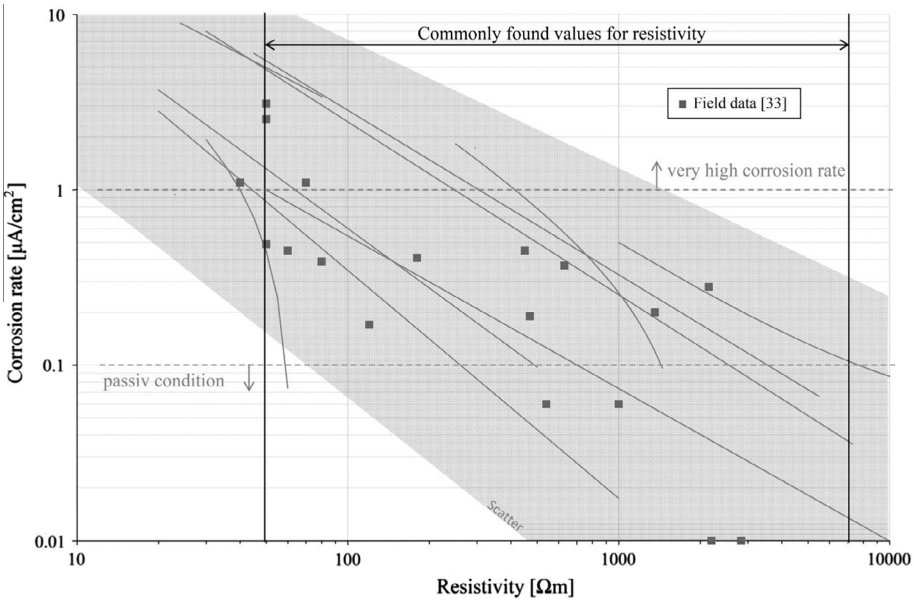

Fig. 6. Scatter within the reviewed studies illustrated as grey cloud around the observed regression lines (details Figs. 4 and 5), compared to field data [32] and framed by upper and lower limits commonly found for corrosion rate and concrete resistivity.

articles. However, when information was provided about the rate limiting step, cathodic control was not observed [5–7]. The influence of the sample's size on the C–R relationship is therefore not considered further in this review.

2.2. Measurement methods

Recommendations for measuring corrosion rate and concrete resistivity have been published [23,35]. However a standardized measuring protocol does not exist for either of them at present.

Recommendations suggest measuring concrete resistance using an alternating current (AC) with a frequency between 50 and 1000 Hz [15]. For low temperatures and high moisture contents, frequencies in a higher range of 100 Hz to 10 kHz have been recommended [36]. Either 2-electrode or 4-electrode (Wenner) techniques are employed to record the resistance (R (Ω)) [23,37,38], which is transformed into resistivity (ρ (Ω m)) by multiplying it with an appropriate geometrical factor (k (m)).

$$\rho = (U/I) \cdot k = R \cdot k \tag{1}$$

where U is the potential (V) and I is the current (A). The k-value is dependent on the volume covered by the measurements.

The resistivity of concrete is influenced by a variety of parameters and is susceptible to moisture changes in particular (Section 1.1). Chloride ions decrease the resistivity [11], whereas carbonation causes an increase of concrete resistance [39]. Moisture changes, the penetration of chlorides and carbonation takes place mainly in the cover concrete. Accordingly, the concrete resistivity is likely to change over the cover depth and might be considerably different to the resistivity at the depth of the reinforcement. Depending on the expected impact of resistivity on the corrosion process, either the cover resistance or the resistivity at the depth of the reinforcement must be recorded to allow for an accurate comparison with the corrosion rate (Section 1.2). A further problem is that in the case of general corrosion, the resistance of the interfacial transition zone (ITZ) between bulk concrete and steel is of more importance than the bulk resistivity [40]. It is unknown to which extent the resistance of the ITZ can be compared to the bulk resistivity. It is of significance to acknowledge these resistivity differences in the interpretation of the findings. In the reviewed experimental investigations, the concrete resistivity was measured at the level of the reinforcement in most cases (Table 5). The cover resistivity was recorded in part of the studies, where an external LPR device was used to measure the corrosion rate, e.g. [14]. Reference samples to measure resistivity were used in one case [10]. It has to be considered that the concrete resistance measured in parts of the experiment is not accounting for the resistance which influences the corrosion process. The mistake made is dependent on the variation between cover, bulk and local concrete resistivity in the particular experiment, as well as the influence of each on the corrosion process.

Several methods exist to measure corrosion rates in concrete [12]; the most frequently used is the linear polarization resistance (LPR) method, a non-destructive technique. In all reviewed papers, the corrosion rate was determined by LPR, with differences in the arrangement of the measurement setup. The LPR method is based on the observation that the polarization curve near the corrosion potential is linear. A small current is applied from a counter electrode (CE) and the amount required to achieve a defined variation of the potential is recorded. The potential is monitored with a reference electrode (RE). The instantaneous polarization resistance can be calculated from the measurement and transformed into the total corrosion current (I_{corr}) with help of the Stern–Geary equation [41]. The corrosion rate i_{corr} (current density) is obtained by dividing the total corrosion current I_{corr} by the corroding area. Although simple in its theory, the LPR technique meets several challenges in practice [12,42–44].

The amount of corroded surface area is unknown in most measurement situations. It is thus common practice to determine the corrosion rate by dividing the total corrosion current by the area which is affected by the measurement. This calculation may be adequate for uniform corrosion where large parts of the surface area are corroded. However, in the case of localized corrosion only comparatively small pits are affected by corrosion. The local current density inside a pit is significantly higher than the average value for the steel area affected by the measurement. Consequently, the corrosion rate will be underestimated in these cases. The latter must be considered for the reviewed experimental data in the case of localized corrosion as the actual corroding area was unknown in all experiments.

The concrete resistance between the RE and the WE (working electrode, here corroding steel bar) can have a considerable influence on the measured polarization resistance, referred to as ohmic drop. A major error can be made in situations where the concrete resistivity is relatively high. For these cases, the polarization resistance might reflect the concrete resistance rather than the corrosion rate. To avoid this influence, it is commonly suggested to correct LPR measurements for ohmic drop [45]. In parts of the reviewed experiments either no modifications for ohmic drop were done or no information about this was given [4,9,13]. Neglecting the ohmic drop will lead to an underestimation of the corrosion rate. This must be considered as the review moves forward to discuss the results from these studies.

A variety of further parameters not named here can be identified which influence corrosion rate and concrete resistivity measurements, such as confinement techniques, sweep rate, delay time and others [44,46,47]. Only by examining all effects influencing corrosion rate and concrete resistivity measurements can differences observed between studies be explained.

2.3. Materials and exposure conditions

In most experiments, mortar or concrete samples were investigated with a *w*/*b* ratio between 0.4 and 0.65 by mass (Table 6). The mixture proportions and cement content varied. Only one work used higher *w*/*b* ratios of 0.9 and 1.1, to achieve a fast change of the internal environment when changing the exposure [16]. Such high *w*/*b* ratios are not related to current practice. Blended cements such as fly ash or slag cements were used in parts of the studies [4,5,10,13]. No detailed information was given about the cement type in [6,9,16,20]. It is supposed that ordinary Portland cement was used for these cases, as otherwise a comment would have been expected.

The specimens were exposed to different and/or changing exposure conditions over the testing period (Table 7). In most studies, the samples were exposed to a high relative humidity (RH), as it is known that a RH between 90% and 95% favors high corrosion rates [13]. To achieve a wide range of concrete resistivities, the samples were exposed to drier climates occasionally. Samples were exposed to outside conditions, in particular sea climates, in parts of the studies [13,14,16]. The temperature did not vary considerably in most experiments. In general, experiments were undertaken over a period between one and 5 years.

To evaluate the applicability, limitation and scatter of the C–R relationship sufficiently, it is desirable to cover a wide range of values for both parameters. This can be done by changing both materials and exposure conditions. However, to distinguish the effect of material and exposure, it is of importance that both can be explicitly separated from one another. This can be done by using parallel setups of material mixes and exposing them to varying environmental regimes. Both material and exposure were changed in the majority of the reviewed studies; in most cases, the exposure was changed equally for all samples. This allows an evaluation of the influence of material on the C–R relationship, however no information could be observed about the dependency of different exposure regimes/histories on the C–R relationship in these cases. Information about that was solely provided in [6,9,13].

2.4. Corrosion initiation

Chloride-induced corrosion was investigated in the majority of the studies (Table 8). Just one study concentrated solely on carbonation-induced corrosion [5]. A mix of exposure to chlorides and carbonation was considered in two experiments [7,13]. Chloride-induced corrosion was initiated by mixed-in chlorides in most cases. Cyclic exposure to chloride solution was used just partly. Carbonation was accelerated by storage in carbonation cabinets with a high CO_2 concentration and low RH.

The way corrosion is induced is of importance when experimental results should be related to practice. The initiation of corrosion and the exposure conditions in the reported studies differ from one another. Corrosion initiated by mixed-in chlorides was the most frequently used method. This reduces the time to depassivation (Fig. 1), however mixed-in chlorides may also lead to significant changes in the pore structure of the concrete [11] and the corrosion process [48]. Differences between studies with and without mixed-in chlorides by using the same mix design might be explained due to this influence.

2.5. Summary

The experimental setup can have a considerable influence on the C–R relationship observed, as was shown in the previous sections. In particular the measurement methods comprise a variety of parameters influencing the recorded data. The specimen geometry and the general setup have a minor influence on the results in the opinion of the authors. To allow for a sufficient overview of factors affecting the C–R relationship, the material and exposure conditions should carefully be chosen. Practice related results are in any case desirable and the initiation of corrosion must be selected accordingly. This is favorable in particular for experimental results that should be used as input in prediction models. Subjects discussed above must carefully be taken into account when designing and/or evaluating an experimental setup.

A standardized method would be advantageous for testing the C–R relationship. It would then be possible to compare experimental data obtained in different laboratories and conditions. Such a method should assure practice-related materials and exposure conditions. Just one study reporting field data was identified by the authors [32]. An extensive field survey of the C–R relationship is critically needed to identify possible deviations between laboratory studies and reality.

3. Analysis and scatter

An inverse proportional relationship between corrosion rate and concrete resistivity was observed in all experimental investigations. However, variations occur between studies. Differences between the reports concerning analysis of the data will be discussed in following section. The scatter of the relationship will also be addressed.

3.1. Properties, scales and correlations

The propagation of the corrosion process was described by the corrosion rate in all studies with the exception of [6] where the polarization resistance was not transformed into i_{corr} (Table 9). In the publications, either resistivity ρ (resistance R) or conductivity σ was used. Different scales were chosen to illustrate the C–R relationship depending on the chosen properties. A log–log scale was selected in studies where resistance or resistivity was compared with the corrosion rate. This was done for the majority of the studies (Table 9). Linear scaled axes were preferred in cases where conductivity was correlated with corrosion rate. Other axis types are seldom used for these properties [4,6,14]. A linear regression line was fitted to the experimental data in most studies [4–7,10,13,16,20]. This was done in both the log–log and the linear–linear scales.

Data is fitted in a different way dependent on the used scale. The individual data points are weighed differently and consequently, the trend lines differ. A linear regression line fitted to data using linear scales and not passing though the origin is not resulting in a linear line in the log–log scale (trend lines [13] Fig. 4). It can also be observed that trend lines fitted to data in different scales might correlate differently to each other dependent on the scale. As an example, the regression lines of studies [9,16] have approximately the same slope and location illustrated in linear scales (Fig. 5). However, on the log–log scale (Fig. 4) different slopes and positions are identified.

There exists not one clear single linear correlation between corrosion rate and concrete resistivity, as can be seen when comparing the linear trend lines (Figs. 4 and 5). The regression lines differ from one another in both figures. The slopes of regression lines in the linear–linear scale vary considerably (Fig. 5), whereas in the log–log scale trend lines are shifted in parallel (Fig. 4). Different parameters causing this deviation are identified and discussed (Fig. 3).

Table 10
Assessment of corrosion conditions [45].

	i_{corr}
Passive condition	<0.1 μA/cm^2
Low – moderate	0.1–0.5 μA/cm^2
Intermediate – high	0.5–1 μA/cm^2
Very high	>1 μA/cm^2

In the light of the variation between the trend lines, the impact of different scales to analyze the data is small and so this issue will not be stressed any further.

3.2. Scatter

A sufficient amount of data is needed to evaluate the scatter of the trend lines for the C–R relationship. The number of specimens produced for the reviewed experiments differs from 2 to 40 and consequently also the amount of recorded data (Table 4). A scatter of more than one order of magnitude was observed for the corrosion rate for parts of the individual data sets [5–7,16,20,32]. Assessment criteria for corrosion activity distinguish one order of magnitude between very high corrosion activity and passive conditions (Table 10). This should serve as a warning not to rely solely on a given regression line to characterize the C–R relationship.

The general scatter of the data reviewed is illustrated in Fig. 6 as a grey cloud around the regression lines. The borders of resistivity values commonly found in the field [23] are plotted in addition to the classification of the corrosion rate (Fig. 6). In the light of this frame, it becomes apparent that the C–R relationship can be utilized just by understanding the reason for its variation. Otherwise, the clear trend observed for the C–R relationship diminishes to a data cloud.

Field data collected at one building during a period of a half year is plotted as grey squares in Fig. 6 [32]. The scatter of the field data encompasses all trend lines. This demonstrates the difficulties faced when trying to assess the corrosion rate in an accurate way by measuring concrete resistance in the field.

3.3. Summary

The scale in which the experimental data is analyzed influences the regression lines and their comparison. However, this impact on the C–R relationship vanishes in the light of the high scatter observed for the individual data and between the regression lines. To allow for an application of the C–R relationship in practice, it is essential to explain its scatter and variation.

4. Dependency and limitation

The question of which parameters the C–R relationship depends on, is of high interest in the light of the observed variation between the regression lines. To address this variation, this section evaluates the influence of material and exposure on the relationship. The discussion is based on the reported regression lines (Figs. 4 and 5).

4.1. Materials

The dependency of the C–R relationship on concrete properties is explained with contradictory hypotheses in the literature. No changes of the correlation were experienced in some studies [4,16] by changing the *w*/*b* ratio from 0.4 to 0.6 or replacing parts of the cement by slag. In other cases, changing *w*/*b* ratio and/or cement type influenced the observed trend lines [10,13]. Variations in the slopes of the regression lines were observed for data from carbonated samples prepared with different cement types [5], in particular a difference can be seen between OPC and the other cement types (Table 11). However, in the study it was concluded that the values are in good agreement and that a general relationship between corrosion rate and concrete resistivity can be established [5].

Regression patterns observed for samples made of different cement types are marked with different line types for the case of chloride induced corrosion (Figs. 4 and 5) (Table 3). Based on this, a gap can be observed between trend lines found for OPC (dashed doted lines) and for slag cements (dashed lines), with the exception of one study [20]. Although OPC was used in the latter study [20], the trend line is clearly differing in position from the lines observed for other OPC samples. Variations within the two groups of trend lines can also be observed. This might be explained by differences in the amounts of slag used or different *w*/*b* ratios. Another explanation might be variations in the experimental setups, such as the manner in which chlorides were induced or the measurement methods (Section 2). Setting aside these factors, it might be concluded that the C–R relationship is dependent on the cement type in the case of chloride-induced corrosion.

One regression line clearly deviates from the pattern described above (Figs. 4 and 5 trend line for [20]). The samples investigated in this study were more than 10 years old and stored in a dry laboratory climate during these years [20]. It is very likely that large parts of the concrete cover were carbonated when comparing the conditions to similar reports [1]. Carbonation leads to a densification of the concrete pore structure for concrete made of OPC and a decrease of the pH in the pore solution [1]. Also the type of corrosion might be changed which will be discussed as the review moves forward (Section 4.3). Both could be an explanation for the deviation of this regression line. Similar observations were made on samples exposed to accelerated carbonation. The C–R relationship changed noticeably after this treatment [13]. It can thus be concluded that not only the cement type but also carbonation of the concrete cover, might influence the trend lines found for the C–R relationship.

Just two data series could be compared for corrosion due to carbonation (Figs. 4 and 5). The regression line for the mix prepared with slag cement [13] is located somewhat higher than the trend line observed as an average of different cement types [5]. A variation between OPC samples and samples made of other cement types were observed for the latter data series (Table 11), as discussed earlier. Consequently, it might be concluded that the cement type has an influence on the C–R relationship also in the case of carbonate-induced corrosion. It cannot be deduced whether this variation is more or less pronounced than in the case of chloride-induced corrosion, because of the limited amount of data.

4.2. Exposure

The impact of humidity and temperature on the C–R relationship was emphasized in just a few studies (Section 2.3). The influence of exposure was discussed separately for corrosion rate and concrete resistivity in [13]. It was reported that both corrosion rate and concrete resistivity are influenced exponentially by relative humidity and temperature under homogenous material conditions. This suggests that the corrosion rate can be studied by measuring concrete resistivity, once the C–R relationship is established for specific material conditions [13,49–51]. Contradicting this, an a priori relationship between corrosion rate and concrete resistivity was excluded for chloride-induced corrosion in [28]. In this case, it was found that corrosion rate showed a higher dependency on temperature than concrete resistance does. This statement is supported by comparing activation energies found for the corrosion process and concrete resistivity in literature. Commonly the corrosion process shows activation energies around 30–40 kJ/mol (in the range of 85–100% RH and temperatures between 0 and 60 °C) [52]. Resistivity, on the contrary, appears to have a lower temperature dependency with activation energies in the average of 25 kJ/mol (calculated from the constant A in Hinrichson-Rasch Law multiplied with the ideal gas constant) [11].

The complex correlation between climate variables (as temperature and relative humidity) and corrosion rate was also discussed in [53]. It appear from the paper that the complex dependency of corrosion rate on temperature and moisture state could best be correlated to changes in the concrete resistivity [53].

The influence of the degree of moisture saturation of concrete on the C–R relationship was described in [9]. It was stated that the C–R relationship is just applicable for moisture contents below 70% degree of pore saturation under the specific experimental conditions [9]. For concretes with some capillary porosity, this might be in agreement with [6] where it was stated that the C–R relationship is not valid for concrete near water saturation or above an atmospheric relative humidity of approximately 95% [6].

Very little information about the influence of exposure on the C–R relationship can be observed from the graphical comparison. Regression lines found for data from samples with the same mix composition (Table 6) but different exposure conditions (Table 7) show a good correlation, such as data from [9,16]. Based on the data available, it may be concluded that the exposure conditions are of minor importance on the C–R relationship, supporting the findings in [13]. However, there is a need for further research in this area.

4.3. Corrosion mechanism

The anodic, cathodic and concrete resistance will influence the corrosion rate to a varying degree (Fig. 2), depending on environmental and material conditions. Without the presence of chlorides or in non-carbonated concrete, the anodic resistance will be high and prevent corrosion onset. In a submerged structure, oxygen supply is limited and consequently the cathodic reaction will be slow, even though, e.g. a sufficient amount of chloride is present. In contrast, in very dry environments, the high concrete resistance will inhibit the corrosion rate. Between these extremes, the rate limiting step is more undefined. To what extent corrosion rate

Table 11
Slopes of trend lines obtained in [20] – lg i_{corr} = lg i_o + slope lg ρ.

Type of mortar	OPC	Sulfate resistance PC	Slag cement	Pozzolanic cement	OPC + 30% FA	Fly ash cement
Slope	−0.72	−1.11	−1.07	−1.06	−1.08	−1.06

can be correlated to concrete resistance will depend on its influence on the rate limiting step.

Corrosion can be initiated by chlorides or carbonation (Section 1.2). Carbonation will lead to a general type of corrosion with anode and cathode sites immediately adjacent to one another. The current will primarily flow through the interfacial zone between the steel and the bulk concrete [40]. On the contrary, chloride-induced corrosion results in localized pits and, anode and cathode areas are separated in space from one another. The current field which develops between anode and cathode will span through the bulk concrete, but is forced to flow through the pit mouth. Dependent on the pit size, the spreading resistance of this bottleneck to current flow can be very high [33].

For general corrosion due to carbonation, it is proposed that concrete conductivity has an indirect impact on the anodic reaction rate, which limits the corrosion rate. This is termed "anodic resistance control" and is comparable to diffusion or activation polarization under other conditions [7,13]. Contradicting this assumption, theoretical analyses of the corrosion process of general corrosion showed that cathodic activation control might also be considered as a rate limiting step for general corrosion [40]. The resistance of the concrete between anode and cathode areas was not identified to be rate limiting as they are in close proximity of each other and thus the concrete resistance is low. Anodic and cathodic reactions are primarily dependent on the transport through the cover concrete. Consequently, the resistivity of the cover concrete should be compared to the corrosion rate.

For localized corrosion, the mechanism of corrosion control is unclear [13]. Cathodic control was considered as unlikely, particular in the beginning of pit growth [6,33]. An indirect correlation of concrete resistance to the corrosion rate is expected, comparable to what was explained for generalized corrosion. Primarily, the resistance of the bottleneck to ion flow, such as the supply of chlorides into the pit, will inhibit the anodic reaction rate [33]. The extent to which the resistance of the bottleneck can be compared to the bulk resistivity of the concrete is unknown. The influence of the bottleneck will diminish as the pit grows [33]. For later stages, where big pits and high corrosion rates were obtained, it was suggested that rather a mix or pure cathodic control limits the corrosion process [54]. Accordingly, the rate limiting step might change over the course of the corrosion process. This and the unknown relationship between the bottleneck resistance and the bulk concrete resistivity might be a reason that the C–R relationship is less well-defined in the case of chlorides than for carbonation-induced corrosion [13].

Bound chlorides will be released when concrete carbonates. A high amount of chlorides may involve a larger area in the corrosion attack and thus the corrosion rate will be increased [1]. The morphology of pitting corrosion will be less pronounced [1]. This explains the shift of the regression lines observed for carbonated samples prepared with mixed-in chlorides in the direction of higher corrosion rates compared to uncarbonated samples of the same type [13,20] (Figs. 4 and 5). Carbonation seems to have a pronounced effect for samples prepared with OPC; the same is not observed for samples made with slag blended cements [13] (Figs. 4 and 5). An explanation for this might be the difference in the impact of carbonation on OPC and slag concrete. The resistivity of OPC increases due to a combination of reduced pore solution conductivity and porosity. For slag cement, carbonation increases the porosity and thereby contradicts the impact of reduced pore solution conductivity.

Interesting to notice is that in the graphical comparison of the regression lines mainly two areas can be identified where the trend lines gather (Figs. 4 and 5). The first group presents regression lines from carbonated samples and samples made of slag cement. The second group corresponds to trend lines found for samples made with OPC suffering from chloride-induced corrosion. It would be of high interest to study whether these groupings are the result of different corrosion morphology and rate limiting steps or a simple coincidence. Unfortunately, no detailed information about the type of corrosion or rate limiting step was given or obtained in the reviewed literature.

4.4. Summary

Cement type was, in particular, identified to have an influence on the C–R relationship. This seems to be pronounced in the case of chloride-induced corrosion. A distinct difference was observed between regression lines for carbonated and uncarbonated samples prepared with OPC. More research is needed to evaluate the influence of moisture and temperature. They seem to be of minor importance according to the comparison of the trend lines, though doubts were raised concerning the applicability of the C–R relationship in the case of chloride-induced corrosion for temperature changes. It has been emphasized by many authors that the C–R relationship is not valid for the extreme case of concrete near water saturation.

An urgent need for research was identified to be the general understanding of the corrosion process. Without detailed knowledge about the corrosion morphology and the rate limiting step, the exact influence of concrete resistivity on the corrosion process cannot be identified.

5. Models of the propagation period

It is of interest to assess and predict the corrosion process for both existing and new concrete structures. A variety of different forecast models exist helping to estimate the Service Life of structures exposed to severe climates [55,56]. The C–R relationship is a central part of several of these models. Two models have been selected and are compared with the reviewed experimental data.

5.1. Models

A Service Life model derived in parts from the results of the experiments described in [5,32] was reported in [57]. The estimation of the propagation time in the model is based on the C–R relationship. Use is made of an effective resistivity ρ_{ef} that is estimated from the resistivity of saturated concrete, adjusted with factors taking into account concrete age and annual climate changes. The correlation between corrosion rate and concrete resistivity is characterized by a factor K_{corr}:

$$i_{\mathrm{corr}} = K_{\mathrm{corr}}/\rho_{\mathrm{ef}} \tag{2}$$

K_{corr} is the constant for the C–R relationship (3×10^4 μA/cm^2 kΩ cm).

The equation does not consider concrete mix design, the cause of corrosion or exposure conditions [57].

Eq. (2) was supplemented with variables that account for the cause of corrosion in the final DuraCrete report [58]. The following equation is proposed for estimations of the propagation period in the model:

$$i_{\mathrm{corr}} = m_o/\rho_c \cdot \alpha^c \cdot F_{\mathrm{cl}}^c \cdot \gamma_v \tag{3}$$

m_o is the constant for the C–R relationship (882 μm·Ω m/year), ρ_c the characteristic value of the resistivity, α^c the characteristic value of the pitting factor, F_{cl}^c the characteristic value of the chloride corrosion rate and γ_v is the partial factor for the cost of mitigation of risk relative to the cost of repair.

Most parameters are dependent on the cause of corrosion or the type of corrosion, with the exception of m_o. Details about the char-

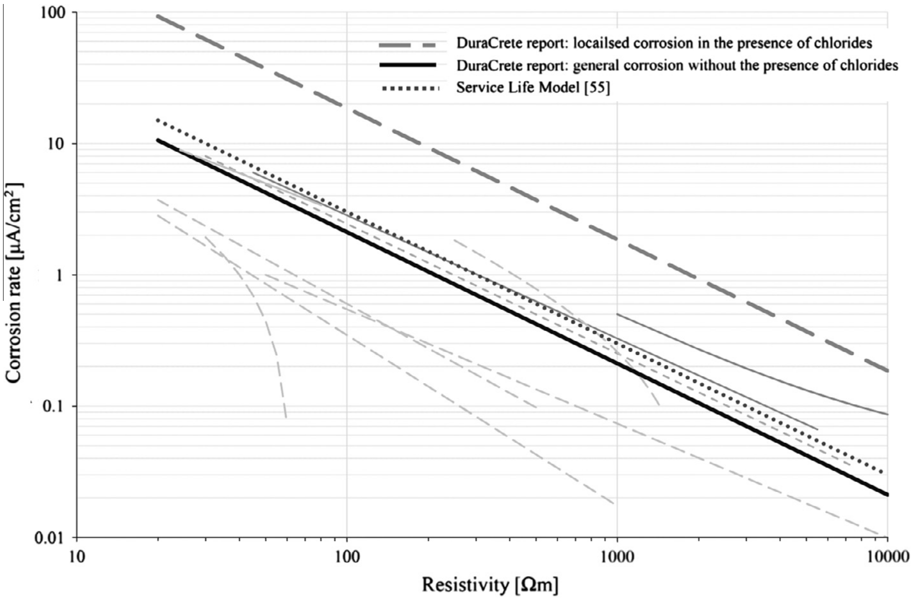

Fig. 7. Comparison between the reviewed Service Life models [57,58] and the regression lines observed in literature (thin dashed lines for chloride induced-corrosion, thin continuous lines for corrosion due to carbonation, details Figs. 4 and 5).

acteristic and statistical quantification of the variables are given in [58,59]. The factors are based on data collected, such as in [13].

5.2. Comparison with experimental investigations

Eqs. (2) and (3) have been compared with the trend lines discussed previously (Fig. 7). The parameters included in the DuraCrete report were chosen for the cases of localized corrosion in the presence of chlorides and for general corrosion without chlorides. The partial factor in Eq. (3) was assumed for a normal relative risk of mitigation costs to repair costs [58].

The computed C–R relationship for corrosion due to carbonation from the DuraCrete report slightly underestimates the corrosion rate compared to the experimental data. However, in the light of the variation observed between the reported trend lines this is seen as a minor deviation. In the case of chloride-induced reinforcement corrosion, the corrosion rate calculated from the DuraCrete report is considerably higher than determined in the experimental investigations (Fig. 7). However, due to the unknown corroding area, it is likely that the corrosion rate was underestimated for localized corrosion in most experiments (Section 2.2). Consequently, the gap observed between the report and the experiments is likely to be smaller and it cannot be assessed whether the report reflects the C–R relationship suitably for localized corrosion. The deviation of the regression lines between the different cement types is not considered in the DuraCrete report, nor is the influence of other parameters such as carbonation of the concrete cover. Additional factors taking into account these influences would be useful.

The model proposed in [57] assumes one single relationship between corrosion rate and concrete resistivity. The presented literature review highlights that this assumption is too simple. Nevertheless, compared with experimental data, Eq. (2) reflects the conditions of carbonated samples and samples made of slag cement suffering from chloride-induced corrosion rather well (Fig. 7). The model should consequently be more specific about its applicability or provide an adjustment of its prediction also for other cases.

The prediction of the models is in good accordance with parts of the experimentally observed regression lines. However, several parameters which might have an influence on the C–R relationship are not considered in the models. None of the models reflected the C–R relationship for chloride-induced corrosion on samples made with OPC as it was observed in the experiments. However, as most of these experiments were undertaken with mixed in chlorides and as the corrosion rate was probably erroneous calculated, it is questionable whether they are representative for practice, see Section 2.4.

It is seen as necessary to refine the equations to be able to predict the C–R relationship sufficiently. In order to enhance and verify the models, more in depth research is needed on factors (such as material, exposure, carbonation of the cover and corrosion mechanism) which have an impact on the C–R relationship and a comparison to practice related data.

6. Summary and conclusions

A clear tendency can be found that with increasing concrete resistivity, the corrosion rate decreases. The relationship can be observed once corrosion has started (active conditions). It will not be valid in the case of saturated concrete, where although the resistivity is low, the corrosion rate will still be small due to a lack of oxygen. Different parameters were identified which might have an influence on the C–R relationship. However, there are still several factors which need intense discussion and investigation. The results of the literature review are summarized in the following.

- Even though a distinct correlation is observed between corrosion rate and concrete resistivity, the scatter observed is high in and between the reviewed investigations (Figs. 4–6). This is reflected also in the ranges suggested for assessment of corrosion activity by means of concrete resistivity (see Table 1).
- The experimental design used to investigate the C–R relationship can have a major impact on the results. Especially, the measurement methods were identified to be susceptible. Corrosion rate measurements should always be corrected for ohmic

drop and for the de facto corroding area, as far as this is possible. The variation between the investigations might partly be explained by differences between the measurement methods.

- The analysis of the experimental data is sensitive to the properties and graphical scales used. It was shown that regression lines found in different scales are not identical. The difference, however, is small compared to the general variation between the trend lines. Nevertheless, it would be desirable for the future to agree upon a concurrent description.
- The scatter of the reported data is relatively high. The probabilistic evaluation of the C–R relationship needs more attention, in particular when it is included in Service Life models.
- The cement type was identified to change the C–R relationship. This was pronounced in the case of corrosion in the presence of chlorides, comparing concretes made of OPC and slag cements. Differences were also observed for carbonated samples prepared with different cement types (chiefly OPC vs. other cement types).
- Carbonation of the concrete cover seems to have an impact on the C–R relationship. Differences were observed between carbonated and non-carbonated samples suffering from chloride-induced corrosion prepared with OPC. The differences for samples made of slag cements were less pronounced. However, more detailed research is needed to strengthen this finding.
- The moisture state and temperature were found to be of minor influence to the C–R relationship, when comparing the same material conditions. However, just a few studies could be used for this comparison and more investigation is needed in this field.
- The cause of corrosion might also be identified to influence the C–R relationship. A gap was observed between samples made of OPC suffering from chloride-induced corrosion and carbonated samples. Unfortunately, no conclusions could be drawn on extent to which the type of corrosion (localized or general) influences the C–R relationship. Different mechanisms underlying these types of corrosion are why a variation of the C–R relationship might be expected. It is highly recommended to study this issue in greater detail.
- The rate limiting step underlying the corrosion process forms the basis of the C–R relationship. To justify and evaluate the applicability of the C–R relationship, it is vital to gain further knowledge about the mechanism which dominates the corrosion process and how it is influenced by the concrete resistance.
- Prediction models risk over-simplifying the complex C–R relationship, owing to the variety of parameters changing and influencing it. Both models discussed here missed detailed differentiation of parameters which have an impact on the C–R relationship.
- Field data was taken into account in just a few studies. It is of high interest to collect further field experience to assess the practicability of the C–R relationship.

It can be concluded that although the concrete resistivity seems promising for the assessment of Service Life of reinforced concrete structures, it is necessary to investigate its relationship to the corrosion rate further.

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