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EMPIRICAL MODELS OF CORROSION RATE PREDICTION OF STEEL IN REINFORCED CONCRETE STRUCTURES

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Abstract

Corrosion rate is one of the most important input parameters in corrosion-induced damage prediction models as well as in calculation of service-life for reinforced concrete structures. In most cases, instantaneous measurements or constant corrosion rate values used in damage prediction models is irrelevant. The new factors appearing such as corrosion-induced cover cracking, concrete quality to change the corrosion rate should be taken into consideration. This study shows several empirical models to predict the corrosion rate and their limits of application. The predicted values of steel corrosion rate using four empirical models are compared with the measured values of a series of 55 experimental samples collected from the literature. The results show that the empirical models overestimated the experimental corrosion rate. Using model proposed by Liu and Weyers provided the best agreement with the experimental data.

Keywords: corrosion rate; prediction model; reinforced concrete; chloride ions; reinforcement corrosion.

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1. Introduction

Corrosion of structural steel in reinforced concrete structure has drawn major interest from well-known authors in recent decades. The process of steel corrosion is illustrated by the general model first proposed by Tuutii K. in 1980 [1]. According to the model, the mentioned process in uncracked concrete can be divided into two stages: (i) initiation phase, in which chloride ions penetrate the concrete cover while the rebars inside are still in a passive state; (ii) propagation phase, in which rebars are corroded due to their exposure to chloride ions after their outer passive layer has been worn away. The majority of prediction models only focus on the first stage (initiation phase) or the chloride ion threshold above which corrosion happens. Few researches have carried out on the propagation phase, especially under the condition where the concrete cover has already cracked due to the applied loads [2].

This study will focus on prediction models of the corrosion rate during the propagation phase. It should be noted that the corrosion rate of steel rebars in concrete structures can be affected by

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diverse factors, namely: temperature, humidity, electrical resistivity of concrete, admixtures, quality of concrete, concrete cover thickness, the loading situation of structure, surface cracks, the intrusion of oxygen, and the direction of structure surface. However, it is impossible to integrate all the above factors into one particular model. Therefore, several factors (e.g. humidity, temperature, quality of concrete) will be indirectly accounted by employing some specific constants.

2. Empirical models for corrosion rate prediction

2.1. Alonso et al.'s model (1988) [3]

This was the first time, Alonso et al. [3] presented a prediction model of corrosion rate that was based on a statistical analysis of concrete electrical resistivity. Mortar samples having the dimensions of $20 \times 55 \times 80$ mm were made of different types of cement with the same water-cement ratio w/c of 0.5. The corrosion rate was accelerated using a CO_2 chamber (100% concentration) with relative humidity (RH) of 50 - 70%. Instantaneous corrosion current i_{corr} was measured by using the LPR technique (Linear Polarisation Resistance) and then determined by the gravimetric analysis method. The relation between i_{corr} (μA/cm^2) and electrical resistivity of concrete ρ_{ef} is described in Eq. (1) with $k_{corr} = 3 \times 10^4$ μA/cm^2.kΩ-cm.

$$i_{corr} = \frac{k_{corr}}{\rho_{ef}} \tag{1}$$

Eq. (1) which was formulated for a CO_2 filled environment similar to the condition under which corrosion happens in the atmosphere, presents the direct relationship between i_{corr} and ρ_{ef}. However, Alonso et al.'s model has a few major flaws: (a) i_{corr} is not only affected by electrical resistivity of concrete but also by the appearance of newly formed cracks during the corrosion process; (b) i_{corr} can also be affected by the thickness of the concrete cover; (c) the equation can be only used for corrosion in atmospheric conditions, which tend to take years before reaching the propagation phase. Therefore, it is not applicable for predicting corrosion rate in chloride environment, in which the propagation phase can occur very early.

2.2. Yalcyn and Ergun's model (1996) [4]

Used cylindrical samples of concrete had the dimensions of 150 mm in diameter, 150 mm in height and were mixed with salt during the manufacturing process. The tested samples were made of Pozzolan cement. The corrosion current was measured using the HCP technique (Half Cell Potential) and LPR technique at 1, 7, 28, 60 and 90 days. Yalcyn and Ergun's model [4] shows the relation between the corrosion rate i_{corr} (μA/cm^2) and time Θ in Eq. (2), with i_0 being the initial corrosion rate, C being a constant relating to the thickness of the concrete cover, permeability, pH and water saturation of concrete. In this experiment, the authors used only one value of C as 1.1×10^{-3} day^{-1} for all cases.

$$i_{corr} = i_0 e^{-C\Theta} \tag{2}$$

This model was deduced based on experiments on accelerated corrosion, not natural or nearly natural corrosion. In reality, chloride ions would have to be removed from the concrete structures. Therefore, the model fails to reflect the corrosion process in real-life cases (the initiation phase had been bypassed in this experiment). The model can only be applied to uncracked concrete structures. With pre-cracked concrete structures, it may not be appropriate to apply this model due to the drastic influence of cracks on both initiation and propagation phases. The model also implies that the value of i_{corr} depends solely on the variable of time and not including other parameters (e.g. environmental conditions) and thus, incorrectly reflecting the nature of the corrosion process.

2.3. Liu and Weyers's model (1998) [5]

In a more expansive research of Liu and Weyers [5], the authors based on experimental results from 2927 sets of data from 7 series of chloride-exposed samples that were experimented in outdoor conditions for 5 years, had proposed the following prediction model for corrosion rate i_{corr} (μA/cm^2) as Eq.(3).

$$i_{corr} = 0.926 \exp\left[7.98 + 0.7771 \ln(1.69C_t) - \frac{3006}{T} - 0.000116R_c + 2.24t^{-0.215}\right] \tag{3}$$

Eq. (3) reveals the fact that the corrosion process of steel rebars in regular service environments relates to the chloride content C_t (kg/m^3), temperature T (K) at the surface of steel rebars, electrical resistivity of the concrete cover R_c (Ωs), and the corrosion time t (years). Similar to Yalcyn and Ergun's model [4], Eq. (3) is based on experimental results of tested samples that consisting of the addition of salt to the concrete mixture and therefore it is only applicable to a specific stage of the corrosion process. However, this model denies the reliance of corrosion rate on the thickness of the concrete cover and the humidity of the environment. Moreover, the model also does not distinguish the two major stages of corrosion.

The electrical resistivity of concrete can be determined using the following empirical formula:

$$R_c = \exp\left[8.03 - 0.54 \ln(1 + 1.69C_t)\right] \tag{4}$$

2.4. Vu and Stewart's model (2000) [6]

Vu and Stewart [6] presented a prediction model based on the assumption that the corrosion rate was determined by the consumption of oxygen on the surface of rebars. Thus, the corrosion rate i_{corr} would be a function of the quality and the thickness of the concrete cover ($w/c, C$). This assumption is reasonable only in particular parts of Australia, America, Europe and Asia where humidity levels are quite high (above 70%). In fact, those are only two amongst a multitude of factors affecting the speed of the corrosion process. Based on experimental data of different authors, Vu and Stewart proposed a prediction model in Eq. (5) for the corrosion rate denoted $i_{corr(1)}$ during the propagation phase after a year of corroding in chloride environment at 20°C temperature and 75% relative humidity.

$$i_{corr(1)} = \frac{37.8(1 - w/c)^{-1.64}}{C} \tag{5}$$

During the propagation phase of corrosion, the corrosion rate $i_{corr}(t_p)$ is predicted by Eq. (6) with C (cm) being the thickness of the concrete cover, t_p (years) being the current duration of propagation phase.

$$i_{corr}(t_p) = 0.85t_P^{-0.29} i_{corr(1)} \tag{6}$$

The model shown in Eq. (6) possesses significant improvements over models in Eqs. (1), (2) and (3) in that: (a) it clearly distinguishes the two different stages of corrosion; (b) it has taken into consideration the direct impact of the water-cement ratio w/c and the thickness of the concrete cover C on the speed of corrosion; (c) it allows the prediction of corrosion rate during the propagation phase even when the concrete structures are cracked due to corrosion. However, it still has its disadvantages:

the speed of corrosion in the early phases of propagation is not affected by the chloride content on the surface of concrete structures. The model is established on the assumption that the consumption of oxygen greatly influences the speed of corrosion while in chloride environments, strong corrosion can still occur without the presence of a large amount of oxygen.

2.5. DuraCrete model (2000) [7]

The European research project DuraCrete was initiated in 1996 with the involvement of many European countries. The objective was to work out a design and assessment code for reinforced concrete structures. In the Appendix B of DuraCrete introduced a relation between the corrosion rate i_{corr} (µm/year) and influencing factors in Eq. (7) with mo being the constant regarding the relation between corrosion rate and electrical resistivity of concrete, α^c being the value representing pitting corrosion, F_{cl}^c being the value representing chloride corrosion, γ_V being the local coefficient of corrosion, ρ being electrical resistivity of concrete, given by Eq. (8).

$$i_{corr} = \frac{m_0}{\rho}\alpha^c F_{cl}^c \gamma_V \tag{7}$$

$$\rho = \rho_0^c \left(\frac{t_{hydr}}{t_0}\right)^{n_{res}} k_{t,res} k_{c,res} k_{T,res} k_{RH,res} k_{cl,res} \tag{8}$$

where ρ_0^c (Ωm) is the electrical resistivity of concrete at 28 days; t_{hydr} is the duration of cement hydration, which affects ρ_0^c (this normally does not exceed one year); n_{res} is the factor concerning the influence of time on electrical resistivity of concrete; $k_{t,res}, k_{c,res}, k_{T,res}, k_{RH,res}, k_{cl,res}$ are factors concerning the impact of testing method, curing, temperature, humidity and chloride content, respectively.

The value of i_{corr} (µm/year) in Eq. (7) needs to be converted into i_{corr} (µA/cm^2) using a constant of 11.5^{-1} due to the difference in units. The DuraCrete model actually improves on that in Eq. (1) by adding the impact of other factors that affect the speed of corrosion over time. Despite having considered additional factors, Eq. (7) still has some drawbacks similar to those of Eq. (1). The influencing parameters are determined by using probabilistic models and presumed to be constants at the instance.

A major advantage of the DuraCrete model is that it takes into consideration the impact of many actual concerning factors of corrosion environments in order to assess the behavior of corroded structures.

2.6. Pour-Ghaz et al.'s model (2009) [8]

Pour-Ghaz et al. have investigated the effect of temperature on the corrosion rate of steel in concrete using simulated polarization resistance experiments [8]. The simulated experiments were based on the numerical solution of the Laplace's equation with predefined boundary conditions of the problem and have been designed to establish independent correlations among corrosion rate, temperature, kinetic parameters, concrete resistivity and limiting current density for a wide range of possible anode/cathode (A/C) distributions on the reinforcement. The results capture successfully the resistance and diffusion control mechanisms of corrosion as well as the effect of temperature on the kinetic parameters and concrete/pore solution properties, have been used to develop a closed-form regression model in Eq. (9) for the prediction of the average and maximum corrosion rates of steel in concrete.

$$\left\langle \begin{matrix} i_{corr,ave} \\ i_{corr,\max} \end{matrix} \right\rangle = \frac{1}{\tau\rho^{\gamma}} \left(\eta T d^{\kappa} i_L^{\lambda} + \mu T \nu^{i_L^{\varpi}} + \theta (T i_L)^{\upsilon} + \chi \rho^{\gamma} + \zeta\right) \tag{9}$$

where ρ (Ωm) is the concrete resistivity; T (K) is temperature; d (m) is concrete cover thickness and i_L (A/m^2) is the limiting current density. The constants in Eq. (9) are given in Table 1.

Table 1. The constants of Pour-Ghaz et al.'s model in Eq. (9)

$i_{corr,ave}$		$i_{corr,\max}$	
Constant	Value	Constant	Value
τ	$1.181102362 \times 10^{-3}$	τ	1
η	$1.414736274 \times 10^{-5}$	η	0.32006292
ζ	−0.00121155206	ζ	−53.1228606
κ	0.0847693074	κ	0.00550263686
λ	0.130025167	λ	0.120663606
σ	0.800505851	σ	0.787449933
μ	$1.23199829 \times 10^{-11}$	μ	$-3.73825172 \times 10^{-7}$
θ	−0.000102886027	θ	47.2478753
υ	0.475258097	υ	0.00712334564
χ	$5.03368481 \times 10^{-7}$	χ	0.003482058
ν	90487	ν	784679.23
ϖ	0.0721605536	ϖ	0.0102616314

The concrete resistivity at the desired temperature T (K) is calculated by Eq. (10), with ρ_0 being the concrete resistivity at the reference temperature T_0 (K), $R \approx 8.314$ J/(mole K) being the universal gas constant, and ΔU_ρ (kJ/mole) being the activation energy of the Arrhenius relationship (Eq. (11)) that depends on the degree of saturation S_r. Meanwhile, the limiting current density i_L (A/m^2) is estimated for each case by using Eq. (12) as a function of concrete cover d (mm, oxygen diffusion coefficient of concrete D_{O_2} (m^2/s) and amount of dissolved oxygen on the surface of concrete $C^s_{O_2}$ (mole/m^3), with z_c being the number of electrons participating the cathodic reaction and $F = 96500$ C/mole being the Faraday's constant. The D_{O_2} is calculated by the model proposed by Papadakis et al. [9] in Eq. (13), with ε_p being the porosity of hardened cement paste and RH being the relative humidity. The $C^s_{O_2}$ can be estimated by using the relationship between the amount of dissolved oxygen on the surface of concrete and temperature in Eq. (14).

$$\rho = \rho_0 e^{\frac{\Delta U_\rho}{R}\left(\frac{1}{T}-\frac{1}{T_0}\right)} \tag{10}$$

$$\Delta U_\rho = \frac{26.753349}{1 - 4.3362256 \times e^{-5.2488563 S_r}} \tag{11}$$

$$i_L = z_c F \frac{D_{O_2} C^s_{O_2}}{d} \tag{12}$$

$$D_{O_2} = 1.92 \times 10^{-6} \varepsilon_p^{1.8} (1 - RH)^{2.2} \tag{13}$$

$$LnC^s_{O_2} = -139.344 + \frac{1.575 \times 10^5}{T} - \frac{6.642 \times 10^7}{T^2} + \frac{1.244 \times 10^{10}}{T^3} - \frac{8.622 \times 10^{11}}{T^4} \tag{14}$$

Pour-Gahz et al.'s model proposes to use many auxiliary models that are given in the other studies in order to estimate the limiting current density and concrete resistivity. These models consider the porosity, saturation and water-cement ratio in concrete, not including the chloride content. Therefore, the estimated values may have high errors due to the limitations of the model used, such as the lack of influencing parameter on the limiting current density and concrete resistivity, the intrinsic error of the model, etc. Moreover, the calculations of Pour-Gahz et al.'s model are complicated in comparison with the other models.

3. A comparison between predicted values of steel corrosion rate by empirical models and experimental data

This section contains comparisons between the corrosion rates obtained from the literature and from the four models of Liu and Weyers, Vu and Stewart, DuraCrete, and Pour-Ghaz et al. These mod-

Table 2. Synthesis of experimental data from the literature – part 1

Author	Sample	C (mm)	d (mm)	w/c	T (K)	RH (%)	C_t (%)	t (years)	i_{corr} ($\mu A/cm^2$)
Lopez et al. [10]	1	7	6	0.5	273	50	2.0	1.0	0.11
	2	7	6	0.5	273	90	2.0	1.0	0.19
	3	7	6	0.5	273	T.I.	2.0	1.0	0.80
	4	7	6	0.5	303	50	2.0	1.0	0.05
	5	7	6	0.5	303	90	2.0	1.0	2.29
	6	7	6	0.5	303	T.I.	2.0	1.0	1.64
	7	7	6	0.5	323	50	2.0	1.0	0.02
	8	7	6	0.5	323	90	2.0	1.0	2.80
	9	7	6	0.5	323	T.I.	2.0	1.0	6.26
	10	7	6	0.5	273	50	4.0	1.0	0.13
	11	7	6	0.5	273	90	4.0	1.0	1.94
	12	7	6	0.5	273	T.I.	4.0	1.0	0.47
	13	7	6	0.5	303	50	4.0	1.0	0.11
	14	7	6	0.5	303	90	4.0	1.0	2.64
	15	7	6	0.5	303	T.I.	4.0	1.0	6.80
	16	7	6	0.5	323	50	4.0	1.0	0.05
	17	7	6	0.5	323	90	4.0	1.0	1.61
	18	7	6	0.5	323	T.I.	4.0	1.0	0.87
	19	7	6	0.5	273	50	6.0	1.0	0.30
	20	7	6	0.5	273	90	6.0	1.0	0.43
	21	7	6	0.5	273	T.I.	6.0	1.0	0.18
	22	7	6	0.5	303	50	6.0	1.0	0.14
	23	7	6	0.5	303	90	6.0	1.0	1.01
	24	7	6	0.5	303	T.I.	6.0	1.0	2.58
	25	7	6	0.5	323	50	6.0	1.0	0.15
	26	7	6	0.5	323	90	6.0	1.0	1.15
	27	7	6	0.5	323	T.I.	6.0	1.0	7.21
Morris et al. [11]	A	15	10	0.6	287	81	0.78	2.73	0.47
	B	15	10	0.4	287	81	0.43	2.73	0.079
	C	15	10	0.6	287	81	1.65	2.73	4.10
	D	15	10	0.6	287	81	0.16	2.73	0.09
Otieno et al. [12]	PC-40-40-U-L	40	10	0.4	298	50	1.28	2.34	1.78
	PC-40-20-U-L	20	10	0.4	298	50	1.40	2.34	1.85
Jee and Pradhan [13]	OPC 0.45	25	12	0.45	300	65	0.20	1.72	0.27
	OPC 0.50	25	12	0.50	300	65	0.30	1.72	0.53
	OPC 0.55	25	12	0.55	300	65	0.37	1.72	1.75
Luping [14]	M15-1V	30	10	0.48	293	85	1.5	0.7	0.06
	M15-1H	30	10	0.48	293	85	1.5	0.7	0.05
	M30-1V	30	10	0.48	293	85	3.0	0.7	0.21
	M30-1H	30	10	0.48	293	85	3.0	0.7	0.17
	M15-1V	30	10	0.48	293	85	1.5	1.0	0.05
	M30-1V	30	10	0.48	293	85	3.0	1.0	0.18

T.I.: totally immersion in water.

els have been verified appropriately by experimental data used to establish models. However, additional verification of other independent experimental data is required. The two models of Alonso et al. [3], Yalcyn and Ergun [4] are too simple and hence, not included in this section.

The experimental data obtained from the literature [10–15] are synthesized in Table 2 and Table 3, and are characterised by the parameters as follows: the concrete cover thickness C (mm), the diameter of steel rebar d (mm), the water-cement ratio w/c, the temperature T (K), the relative humidity RH (%), the chloride content C_t (% or kg/m^3), the corrosion time t (years) and the corrosion rate measured by experiment i_{corr} (µA/cm^2). There are 55 experimental data that were carried out on different types of testing samples, such as: mortar specimens of dimensions 20 × 55 × 80 mm [10], cylindrical specimens of 150 mm in diameter and 300 mm in length [11]; beam specimens of dimensions 120 × 130×375 mm [12]; prismatic specimens of dimensions 62×62×300 mm [13]; slab specimens of small dimensions 250 × 250 × 70 mm [14]; and, slab specimens of large dimensions 1180 × 1180 × 216 mm [15].

Table 3. Synthesis of experimental data from the literature – part 2

Author	Sample	C (mm)	d (mm)	w/c	T (K)	RH (%)	C_t (kg/m^3)	t (years)	i_{corr} (µA/cm^2)
Liu [15]	1	51	16	0.45	299	70	0.31	0.9	0.072
	2	51	16	0.45	300	70	0.31	0.9	0.095
	3	51	16	0.42	300	70	0.78	0.9	0.147
	4	51	16	0.42	300	70	0.78	0.9	0.173
	5	51	16	0.42	291	70	0.63	0.9	0.065
	6	70	16	0.45	290	63	0.31	1.0	0.052
	7	51	16	0.44	306	70	2.45	1.0	0.210
	8	51	16	0.41	295	70	1.43	1.0	0.093
	9	51	16	0.44	282	70	0.78	1.0	0.111
	10	70	16	0.45	286	63	0.36	0.9	0.055
	11	51	16	0.45	286	63	0.36	0.9	0.055
	12	70	16	0.44	292	75	2.45	0.9	0.129
	13	70	16	0.44	292	75	2.45	0.9	0.146

The values of chloride content in a few tests are presumed to be portions of the weight of cement or concrete. The weight of concrete is presumed to be 2500 kg/m^3, cement used in mentioned tests is the OPC cement, no additional admixture is used. Figs. 1–4 show the ratio i_{model}/i_{exp} between corrosion rates obtained from empirical models and from experiments for a series of 55 experimental data. The experimental results containing all needed information are rarely obtained due to the absence of a few essential parameters. Thus, the results of analyses still need to be verified further on other independent experiments.

Fig. 1 shows that Liu and Weyers's model provides the predicted values of corrosion rate which are closest to the experimental data. The ratio i_{model}/i_{exp} has an average value of 4.86 for a series of 55 experimental data used. However, if the chloride ions content is high enough, from 1.5% to 6.0% [10, 14], the electrical resistivity of concrete will be reduced, and lead to erroneous predictions that are significantly different from the experimental data.

Fig. 2 shows that Vu and Stewart's model provides widely varied results that are substantially larger than the actual values. The ratio i_{model}/i_{exp} has an average value of 50.14 for a series of 55 experimental data used. This value is 10 times more than that of Liu and Weyers's model. The ratio

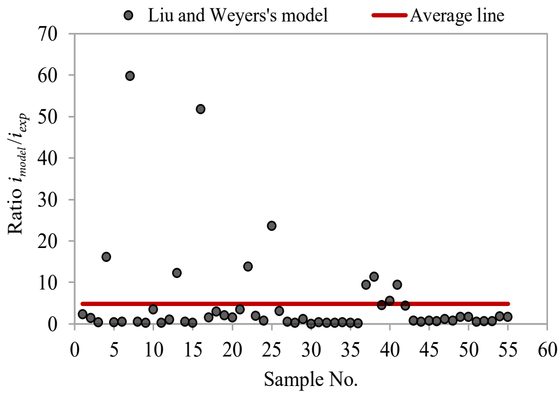

Figure 1. Comparison between the predicted results by Liu and Weyers's model and experimental data

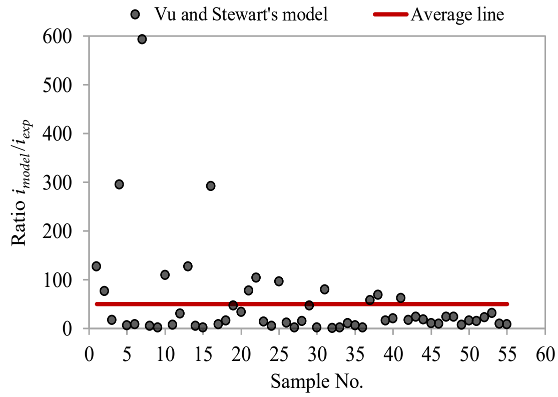

Figure 2. Comparison between the predicted results by Vu and Stewart's model and experimental data

value can reach to 600 on the sample having the chloride content of more than 2%. As mentioned above, this model is rather simple, does not take into consideration many factors concerning the environmental conditions that affect the corrosion rate. It should be noted that this model was established based on experimental results obtained in a specific condition (293°K and 75% humidity).

Fig. 3 presents the results of the ratio i_{model}/i_{exp} for a series of samples when parameters such as $k_{t,res}, k_{c,res}, k_{T,res}, k_{RH,res}, k_{cl,res}, n_{res}, F^c_{cl}, \rho^c_0$ are assigned to be the average values that are presented in a study by Val and Chernin [16]. Additionally, according to DuraCrete model, corrosion rate is also relied on the variable of wet duration which is very hard to control in real life situations. It can be seen that in this case in which parameters are assigned as mentioned, the predicted values of corrosion rate are higher than the experimental values. The ratio i_{model}/i_{exp} has an average value of 21.43 for a series of 55 experimental data used, smaller than that of Vu and Stewart's model, but much higher than that of Liu and Weyers's model.

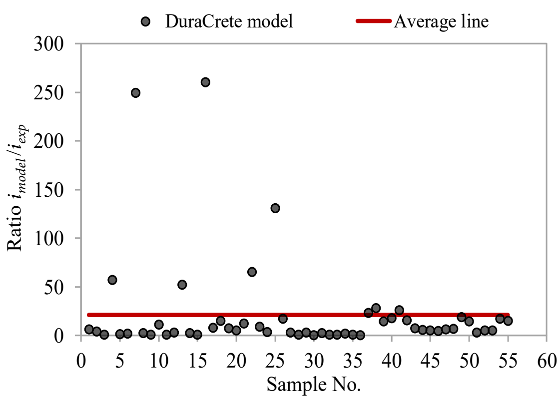

Figure 3. Comparison between the predicted results by Duracrete model and experimental data

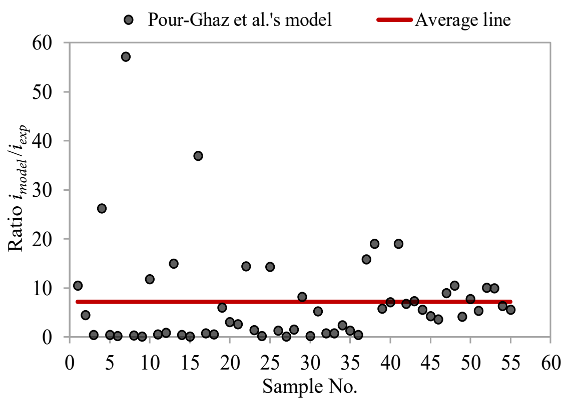

Figure 4. Comparison between the predicted results by Pour-Ghaz et al.'s model and experimental data

Fig. 4 presents the comparison results between the predicted values by Pour-Ghaz et al.'s model for the average corrosion rate and experimental data. In this calculation, the empirical model in Eq. (4) is used to determine the concrete resistivity of the samples, without using the empirical models cited in the study of Pour-Ghaz et al. [8], since these models do not consider the chloride content in concrete samples. The results show that the predicted values of maximum corrosion rate are overestimated. The model of maximum corrosion rate cannot be applied for all samples. Meanwhile, the model of average corrosion rate is acceptable. The ratio i_{model}/i_{exp} has the average value of 7.16 for a series of 55 experimental data used. This value is smaller than that of Vu and Stewart's model and DuraCrete model.

4. Conclusions

This study presents the pros and cons of six empirical models proposed by different authors that are used to predict the corrosion rate of steel in concrete structure occurring in chloride environments. The experimental data collected from separated experiments are compared with the predicted values from the models of Liu and Weyers, Vu and Stewart, DuraCrete and Pour-Ghaz et al. A few conclusions can be drawn as follow:

- In general, all mentioned models provide higher values of corrosion rate compared to actual values from experiments.

- Liu and Weyers's model provides the most accurate prediction of corrosion rate. However, when the chloride content reaches a value ranging from 1.5% to 6.0%, the predicted values can be overestimated in comparison with the actual values.

- Despite its simplicity, Vu and Stewart's model provides excessively higher prediction of steel corrosion rate and thus greatly affects the structure life calculation.

- When using DuraCrete model, a careful consideration must be taken with regard to the input parameters since these values are obtained in a particular condition of experiment and thus, may not be applicable.

- The calculation of Pour-Ghaz et al.'s model is more complicated in comparison with the other models since there are many constants in the formula and it must use the auxiliary models to estimate the limiting current density and concrete resistivity. Their limitation is that they can cause high error in the prediction of corrosion rate. The model of average corrosion rate is acceptable, while the model of maximum corrosion rate cannot be applied in the majority of cases.

The validation of the mentioned models is provisionally acceptable due to the lack of experimental data. Therefore, to apply the models to the climate of Vietnam's region [17, 18] appropriately requires a large-scale, long-term experimentation in order to calibrate existing models or to establish new ones.

References

[1] Tuutti, K. (1980). Service life of structures with regard to corrosion of embedded steel. *Special Publication*, 65:223–236.

[2] Francois, R., Arliguie, G. (1994). Durability of loaded reinforced concrete in chloride environment. *Special Publication*, 145:573–596.

[3] Alonso, C., Andrade, C., Gonzalez, J. A. (1988). Relation between resistivity and corrosion rate of reinforcements in carbonated mortar made with several cement types. *Cement and Concrete Research*, 18 (5):687–698.

[4] Yalcyn, H., Ergun, M. (1996). The prediction of corrosion rates of reinforcing steels in concrete. *Cement and Concrete Research*, 26(10):1593–1599.

[5] Liu, T., Weyers, R. W. (1998). Modeling the dynamic corrosion process in chloride contaminated concrete structures. *Cement and Concrete Research*, 28(3):365–379.

[6] Vu, K. A. T., Stewart, M. G. (2000). Structural reliability of concrete bridges including improved chloride-induced corrosion models. *Structural Safety*, 22(4):313–333.

[7] Duracrete (2000). *Probabilistic performance based durability design of concrete structures*. Document BE95-1347/R17.

[8] Pour-Ghaz, M., Isgor, O. B., Ghods, P. (2009). The effect of temperature on the corrosion of steel in concrete. Part 1: Simulated polarization resistance tests and model development. *Corrosion Science*, 51 (2):415–425.
[9] Papadakis, V. G., Vayenas, C. G., Fardis, M. N. (1991). Physical and chemical characteristics affecting the durability of concrete. *Materials Journal*, 88(2):186–196.
[10] López, W., González, J. A., Andrade, C. (1993). Influence of temperature on the service life of rebars. *Cement and Concrete Research*, 23(5):1130–1140.
[11] Morris, W., Vico, A., Vazquez, M., de Sanchez, S. R. (2002). Corrosion of reinforcing steel evaluated by means of concrete resistivity measurements. *Corrosion Science*, 44(1):81–99.
[12] Otieno, M., Beushausen, H., Alexander, M. (2016). Chloride-induced corrosion of steel in cracked concrete – Part I: Experimental studies under accelerated and natural marine environments. *Cement and Concrete Research*, 79:373–385.
[13] Jee, A. A., Pradhan, B. (2019). Study on development of empirical relationships between durability parameters of concrete made with different types of binder and exposed to chloride environment. *Construction and Building Materials*, 212:799–817.
[14] Luping, T. (2002). *Calibration of the electrochemical methods for the corrosion rate measurement of steel in concrete*. SP Swedish National Testing and Research Institute, SP Building Technology.
[15] Liu, Y. (1996). Modeling the time-to corrosion cracking of the cover concrete in chloride contaminated reinforced concrete structures. PhD thesis, Virginia Polytechnic Institute and State University.
[16] Val, D., Chernin, L. (2008). Service-life performance of reinforced concrete structures in corrosive environments. In *Proceedings of the 1st International Symposium on Life-Cycle Civil Engineering (Biondini F and Frangopol D (eds)). CRC Press, Boca Raton, FL, USA*, 247–252.
[17] Tan, N. N., Dung, T. A., Thế, N. C., Tuan, T. B., Anh, L. T. (2018). An experimental study to identify the influence of reinforcement corrosion on steel-concrete bond stress. *Journal of Science and Technology in Civil Engineering (STCE) - NUCE*, 12(6):29–38.
[18] Nguyen, N. D., Tan, N. N. (2019). Prediction of residual carrying capacity of RC column subjected in-plane axial load considering corroded longitudinal steel bars. *Journal of Science and Technology in Civil Engineering (STCE) - NUCE*, 13(2V):53–62.