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ORIGINAL ARTICLE

A Simple Empirical Model for Predicting Weight Loss of Mild Steel due to Corrosion in NaCl Solution

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ABSTRACT – Validating the degradation rate of construction materials used in public facilities is important for reliability and safety reasons. This is determined through direct measurements using weight loss or electrochemical methods. Both methods, however, are time-consuming and expensive. Therefore the development of a corrosion model for estimating the degradation rate based on weight loss is needed. For this purpose, 25 samples of 80×24×3 mm sized coupons were prepared. The measurements of the weight loss were carried out on the specimens for 10, 20, 30, 40, 50, 60, and 70 days, respectively by total immersion of the samples in NaCl solution of 2, 3, 4, and 5 wt.% with one treated in distilled water. The results show that NaCl concentration significantly influenced the corrosion rate for all variations with an average weight loss value of 1.38 mg/cm^2 and corrosion rate value of 25×10^{-5} mm/year. The proposed empirical model was W_L=0.001*1.34$^{\alpha}$* t$^{0.87}$. In conclusion, the proposed model was successfully established based on the experimental data for predicting the weight loss of mild steel in the NaCl solution.

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Corrosion model, Degradation rate, Weight loss, Mild steel, NaCl solution.

INTRODUCTION

Corrosion is the degradation of material properties, particularly metals due to interactions with the surrounding environment [1-3]. Some natural products capable of creating corrosion are atmospheric, water, and soil. However, amongst the various, the water media has a unique characteristic since it contains various ions, such as Cl^- ion.

It is well-known that the presence of dissolved chloride ions in water accelerates the corrosion reaction [4], as water containing NaCl is classified as a strong electrolyte [5]. The higher the chloride ions concentration, the stronger the nature of the electrolyte, thereby making the electrochemical process of corrosion faster. Another element capable of helping the corrosion process in aqueous media is temperature, oxygen and other oxidizers [6, 7].

Corrosion of steel in seawater environment is widely studied, because of its extensive use and tendency to thin out regularly [8-10]. The tendency for depletion in steel construction exposed to environments containing chloride ions needs to be intensively studied. One method that has been used is to measure the actual thickness described in API 510 [11]. The difference between initial and actual thickness divided by the number of years of construction operation is the corrosion rate. However, the method is not fully effective for estimating the corrosion rate, because it requires measurement of the thickness by each particular period. Therefore a new method which is simpler to estimate the rate of corrosion of steel based on weight loss is needed by knowing the chloride ion content in the solution.

Some researches have already reported the effect of chloride ions concentration toward corrosion rate available in the study done by by Möller et al. [12], Hasan [13], Li [14], May [15], and Ali et al. [16]. They mostly discussed the effect of chloride ions on the corrosion rate experimentally, with limited works studied in a model manner. As noted in the leterature, corrosion models are found mostly for atmospheric corrosion [17,18]. A study on empirical model for steel corrosion in concrete based on field data was done by Lu et al [19]. Corrosion model of steel in water containing Cl-ions has a great potential to be developed using an empirical approach based on the relationship between immersion time and variations in the concentration of NaCl in solution.

Based on the research background, therefore, the objective of this study is to propose a simple empirical model that can predict the weight loss of mild steel due to corrosion in NaCl solution. The proposed model is able to estimate the rate of weight loss of mild steel in water containing NaCl and expressed as corrosion rate. Determining the quality of the environment is one way to estimate mild steel service life by varying concentration of NaCl in the solution and time of immersion during the experiment. The developed model was formulated based on the power-law function.

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METHODS AND MATERIAL

Materials

The materials used in this study were steel plate 80×24×3 mm, and purchased at a steels shop in Banda Aceh, Indonesia. The mechanical properties and chemical composition of the materials are shown in Tables 1 and 2, respectively [16], with its microstructure shown in Figure 1. The chemical composition and its microstructure show that the material is classified as mild steel as evidenced by a carbon content of 0.231 % and the appearance of no dominant alloy. The microstructure of material also shows that the phase composition exhibited dominant ferrite, with the appearance of a very little portion of pearlite. It indicated that the material used was mild or low-carbon steel used in constructing public facility [16].

Table 1. Mechanical properties of mild steel.

Ultimate tensile strength (MPa)	Yield strength (MPa)	Elongation (%)	Young modulus (GPa)	Hardness (HV)
500	354	16	204	142

Table 2. Chemical compositions of mild steel.

C	Si	Mn	P	S	Ni	Cr	Al	Fe
0.231	0.179	0.431	0.005	0.017	0.036	0.016	0.027	Balance

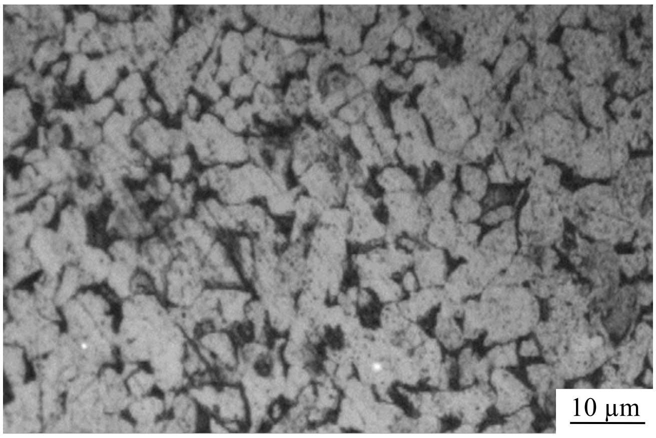

Figure 1. Microstructure of sample used in this study after etching using 5% nital (100 ml ethanol and 5 ml nitric acid) at ×200 magnification.

Samples Preparation

The numbers of the sample used were 25 materials which were divided into five groups of treatment, with every sample immersed in a solution containing 0, 2, 3, 4 and 5 wt.% of NaCl using distilled water as the control variable. During immersion, the solution was supplied with air to ensure it contains oxygen as a precondition of the corrosion process in water. The effects associated with different immersion times and NaCl concentrations on the weight loss of mild steel substrates were investigated. The samples were immersed in different level of corrosive environments and left for a stipulated period of 1680-hours, with a 240-hour interval collecting, weighing, and re-immersing it into the various environments. Data was collected seven times for each observation group. The size and shape of the samples used is shown in Figure 2.

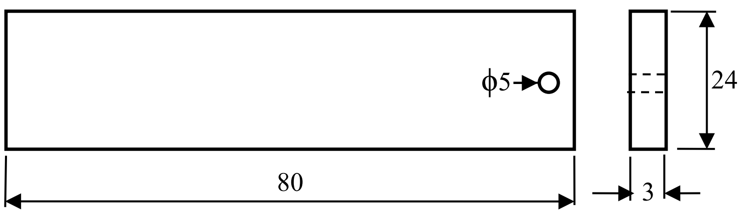

Figure 2. Shape and size of the sample (all dimension in mm).

The samples were sectioned and substracted sequentially using silicon carbide abrasive paper with grit from 180 to 800. The specimens were then washed, cleaned with ethyl alcohol, and dried before it initially weighed to a precision of 3 decimal places before the immersion test was conducted to assess the weight loss data. The samples were immersed in different concentrations of NaCl solution for each interval ten days (a total of 70 days) with corroding media preparation performed in May [15]. In addition to the research objectives described, the corrosion rate of samples due to weight loss during the immersion test was also analysed. NaCl used was in crystal form and was supplied by PT. Garam (Persero) with a purity level of 98-99.9%.

Experimental Procedure

A quantitative analysis method was applied in this study to obtain weight loss data and calculation of the corrosion rate of mild steel samples. The study was performed by totally immersing the coupon samples in the solution with different concentrations of 2, 3, 4 and 5 wt.% of NaCl. The weight loss was measured as a function of immersion time at room temperature (25±2 °C) and an average pH of 7.2. The weight loss data were taken during and after cleaning and carried out according to ASTM G31-72 [20]. The measured data was the weight loss of samples before and after exposure at predetermined times of 10, 20, 30, 40, 50, 60, and 70 days. The cumulative weight loss data were arranged in a matrix form. The logarithmic form of the graph was constructed to elaborate on the relationship of the weight loss and the immersion time for the designed variation of NaCl. Furthermore, the corrosion rate was calculated using Eq. (1) [4, 5, 21]:

$$\text{Corrosion rate, } C_R \text{ (mm/year)} = \frac{87{,}6\ W_L}{A\ t\ \rho} \tag{1}$$

Where: W_L donates the weight loss in milligrams; A donates the cross-sectional area in cm^2, t donates the immersion time in hours; ρ donates density of the sample in g/cm^3, while the cross-sectional area is calculated using the following Eq. (2):

$$A=2\,[(LB)+(BT)+(LT)] \tag{2}$$

Where: L donates the sample length; B donates the sample width, and T donates the thickness of the sample. Data from four types of treatment were used to develop empirical models to predict weight loss based on variations of NaCl. The well-accepted weight loss is expressed in the form of power-law function, as shown in Eq. (3) [14,17,22]:

$$W_L=\eta t^{\beta} \tag{3}$$

Where: W_L donates the weight loss due to corrosion and t is the immersion time that determines the basic corrosion rate of samples. The initial weight loss denoted by η is due to the corrosion observed during the first unit time, and β expresses the measure of the long-term decrease in degradation rate. These constants are directly dependent on the samples, the chemical aquatic and immersion conditions or electrolyte concentration. After obtaining the constants, the next step was to develop the empirical model for predicting weight loss based on the experimental data. The development of the corrosion model was divided into four stages, namely: (1) creating the matrix of measured data of the weight loss: (2) drawing a graph of the weight loss against the immersion time, (3) drawing exponential graph of experimental constants versus concentration of NaCl in wt.%; (4) substituting all values and quantities obtained into the power law function in Eq. (3). After conducting all the processes, the empirical model for prediction of weight loss was obtained as a function of wt.% NaCl and immersion time, t, in hours.

RESULTS AND DISCUSSION

Analysis of the Weight Loss

The effect of NaCl concentration in distilled water and the immersion time on the weight loss was studied in this current work. The weight loss, which is an indicator of the corrosion rate of metals was calculated from the difference of the initial and final weight of the samples. The time immersion affects the weight loss, as well as NaCl concentration because the higher the amount of NaCl concentration in the solution, the higher the weight loss. Also, the longer the material is exposed in the solution, the higher the weight loss. In addition, under the state of high amounts of NaCl, the presence of Cl^- ions is helpful to the formation of FeOOH and $FeCl_2$ as shown in Eq. (4) [1, 15].

$$(F_e{}^{2+}, F_e{}^{3+}) + 2Cl^- + OH^- \rightarrow F_eOOH + F_e\,Cl_2 \tag{4}$$

The tendency of weight loss values leads to the correlation of power-law function (refer to Eq. (3)). Table 3 shows the loss of weight as a function of time and concentration of NaCl. Similarly, the immersion time versus weight loss for various concentrations of NaCl is shown in Figure 3 with the graph drawn in logarithmic form for both axes. This created a slope and yields a value of β=0.87.

Table 3. Weight loss as a function time and NaCl concentration.

Immersion time, t (days)	Weight loss, W_L(mg)				
	Concentration of NaCl (in wt.%)				
	0	2	3	4	5
10	0.206	0.248	0.278	0.298	0.343
20	0.320	0.396	0.446	0.489	0.569
30	0.485	0.563	0.646	0.682	0.766
40	0.686	0.762	0.847	0.885	0.962
50	0.875	1.007	1.079	1.121	1.191
60	1.085	1.197	1.248	1.337	1.395
70	1.225	1.285	1.368	1.474	1.536

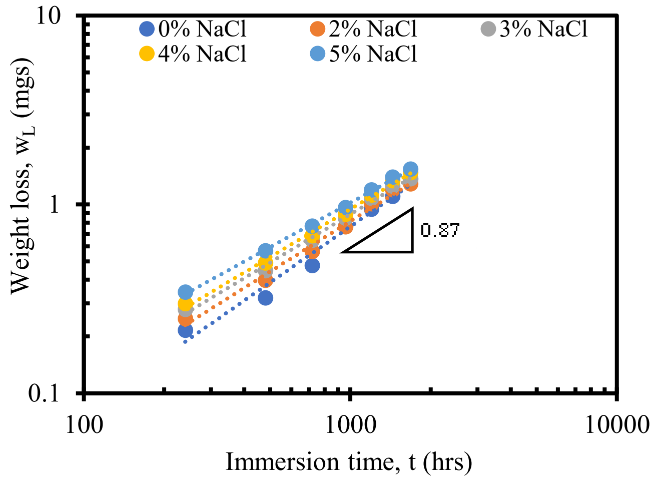

Figure 3. Effect of immersion times on weight loss of mild steel in various of % NaCl

Corrosion Rate Analysis

The rate of corrosion is associated with the chemical reaction between the metal component and the surrounding environment, which includes urban, rural, industry, and marine. Each type of environment has a different level of corrosion. It is known that the marine environment is the most corrosive due to the presence of ion chloride. Steels used in marine environments are subject to chemical, physical, and biological deterioration with resistance to corrosion. The degradation of materials is directly proportional to loss of weight and inversely proportional to the surface area, density, and immersion time as described in Eq. (1). The variations of corrosion rate with the immersion time for various NaCl wt.% concentrations is presented in Figure 4. It can be observed that the corrosion rate decreases with increasing immersion time.

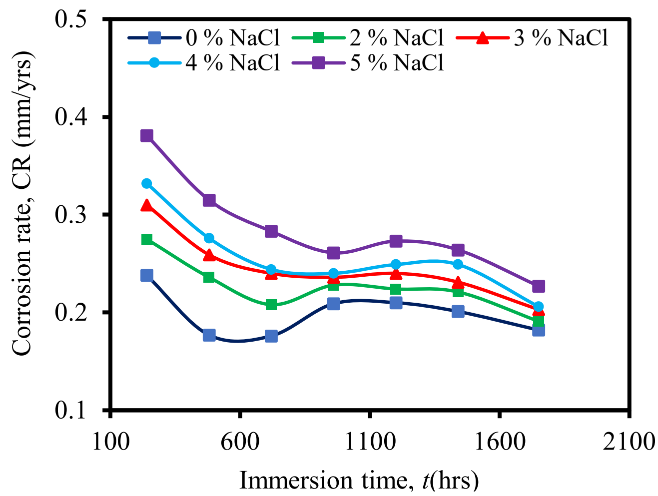

Figure 4. Corrosion rate versus immersion time for various NaCl concentrations.

The corrosion rate of samples in 0% NaCl was recorded to be lower than the samples immersed in 2, 3, 4 and 5 wt.% NaCl. This seems to be in accordance with some of the previous works [14,15]. If the concentration of wt.% NaCl in the solution increased, the corrosion rate of the sample also increased influentially for all periods of observation. The corrosion rate for the first 240 hours of immersion time was high, then decreased when the immersion time reached 960 hours, then the stable stage reached 1440-hours of immersion time and decreased again after 1440-hours. In general, the corrosion rate decreased with an average value in the range of 25×10^{-5} mm/year. It can be concluded that the average corrosion rate showed a decrease below 960-hours when the immersion time, then stabled up to 1440-hours and down to 1680-hours of immersion time was reached. The reduction in corrosion rate was caused by the increasing immersion time while decreasing weight loss remained stable. Therefore, the corrosion rate curve tended to be linearly negative.

Corrosion Model Formulation

An empirical model was developed based on the solubility natures of Fe-ions in electrolytes, which is a function of time derives of Fe ions in the form of weight loss or gain analogous to the function of time. The weight loss experienced by mild steel during its application is expressed as the corrosion rate, according to Eq. (1).

There are several methods for obtaining the corrosion rate, for example, measuring weight loss and using the electrochemical method. The simplest way to measure the corrosion rate of metals is by immersing its samples into the test media (NaCl, seawater) or by measuring the weight loss from the sample as a function of time. The corrosion rate is used to calculate the service life of mild steel samples. Sudjono [23] examined the predictions of the service time of concrete buildings against damages due to corrosion of reinforcing steel.

Estimates of service life for metals directly in contact with electrolytes are modelled more simply using the power-law formula. The medium of corrosion easily react with steel, and the corrosion process takes place all the time. The service time is the period used by the metal or steel to carry out its functions as a mechanical component.

The proposed corrosion model is empirical, which is based on experimental data of the weight loss. This is because the actual corrosion is the weight loss of the materials as functions of time. Assuming it is performed in a large number of variations (e.g., three variations), a correlation tends to develop for the loss of weight versus immersion time for various varieties of NaCl concentration as shown in Figure 3. A power (β) of immersion time (t) with a value of 0.87, is also shown in Figure 3. Therefore, Eq. (3) is rewritten, as shown in Eq. (5).

$$W_L = \eta\, t^{0.87} \quad (5)$$

Furthermore, the results of Figure 3 illustrate the graphs of the regression values for various NaCl concentrations, as shown in Figure 5. The graph derived the constant η with the value of $0.001 * 1.34^{\alpha}$ and R^2 value of 0.945 where α is wt.% of NaCl in solution.

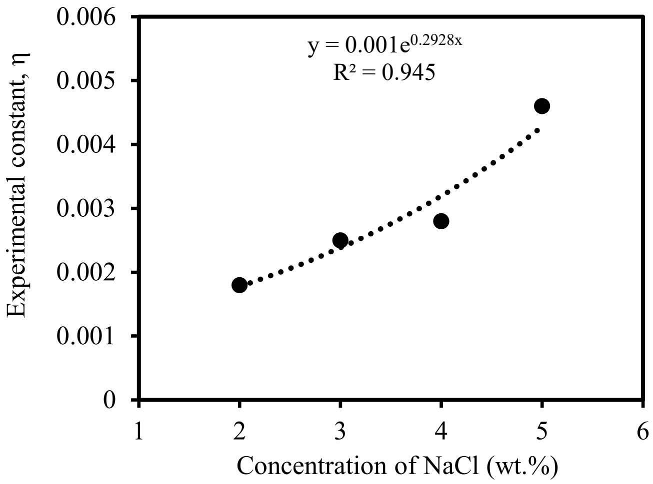

Figure 5. Fitting of experimental constants for various NaCl concentrations

Based on the results of constant experimental fittings for 2, 3, 4 and 5 wt.% of NaCl concentrations, the proposed corrosion model was realised as shown in Eq. (6), where α is the concentration of NaCl and t is immersion time in an hour. Assuming the concentration is known and immersion time simulated, the weight loss of the sample is calculated using Eq. (5). Finally, the corrosion rate of carbon steel is obtained using Eq. (1).

$$W_L = 0.001 * 1.34^{\alpha} * t^{0.87} \quad (6)$$

Model Validation

The proposed model needs to be proven with the available data in the literature to ensure that the formula is robust. Table 4 shows the experimental data in the work of May [15] and from the developed model of current work. The model validation is also shown in Figure 7, which provides a good correlation, and a similar trend is seen from the two lines. The experimental data of the current work is also validated with the proposed model, giving a good agreement. Table 4 presents data of the experimental work of weight loss (WL) and proposed model.

Table 3. A comparison of experimental data result between weight loss [15] and the current model.

Immersion time, t (days)	W_L (mg) [9]	W_L model (mg)	Error (%)
1	0.27	2.41	88.77
7	8.50	13.07	35.00
14	17.40	23.90	27.20
21	40.00	34.01	17.60
28	45.60	43.68	4.38
Average error			34.56

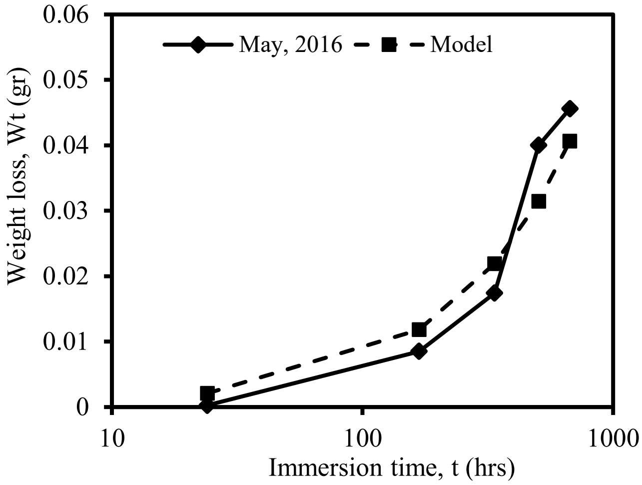

Figure 7. Comparison of the results of the model and experimental work of May [15] for 3 wt.% NaCl in solution.

Figure 7 shows the weight loss of the model in comparing with the experimental work by May, 2016 [15], while Figure 8 expresses the sample's weight loss of model in comparing with the experimental work of the current study. The broken line in Figure 7 and Figure 8 express the model results from Eq. (5). The experimental data were slightly scattered, but the averaged results tend to be an exponential function with error values of 34.56 % and 8.34%, respectively.

Table 4. Comparison of the experimental work of weight loss (W_L) and proposed model

Immersion time, t (hrs)	W_L Experimental work mg)	W_L Model (mg)	Error (%)
240	0.293	0.2748	3.34
480	0.446	0.5094	14.21
720	0.646	0.7307	13.11
960	0.847	0.9439	11.44
1200	1.079	1.1513	6.70
1440	1.248	1.3541	8.51
1680	1.617	1.6516	2.14
Average error			8.49

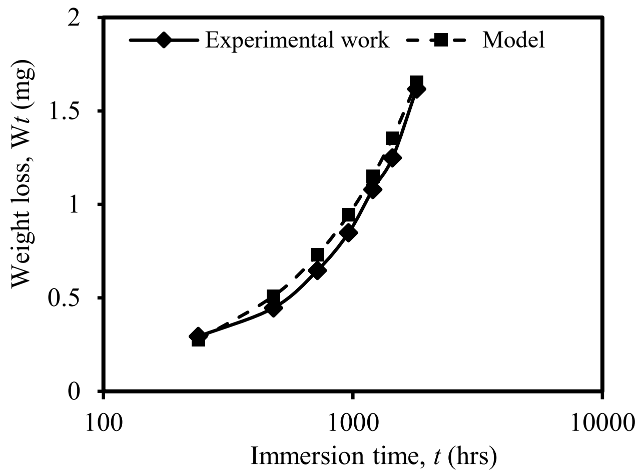

Figure 8. Comparison of the results of the model and the experimental work of the current study for 3 wt.% NaCl.

The model is also applied to verify the valid data of the experimental work for corrosion rate measurement using the weight loss method. Therefore, it is concluded that the empirical and experimental results are comparable and agree. Furthermore, the proposed model to predict the weight loss of mild steel is valid, and therefore, it is the novelty of this research.

CONCLUSION

Based on the research and discussion described, some conclusions are drawn as follows:

i. The empirical model of corrosion degradation has been successfully developed to estimate the weight loss of mild steel. The degradation rate of carbon steel was mainly affected by NaCl concentration with the immersion time estimated using the power-law function, $W_L=0.001*1.34^{\alpha}*t^{0.87}$. The weight loss of the proposed model was validated using the available and experimental data of the current work.
ii. Sodium chloride (NaCl) concentration significantly influenced the degradation rate for all variations of the solution, with an average weight loss value of 1.38 mg/cm^2 and corrosion rate value of 25×10^{-5} mm/year.
iii. The corrosion model which developed the current work involves Cl^- ion. It is possible in future research to develop corrosion models that take into account more variables, such as temperature, oxygen, and other oxidisers.

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