Chapter 10
(Mathematical) Modelling of MIC by Fuzzy Logic

Abstract For a rather complex phenomenon like MIC that not only involves the interaction bwteen lifeless elements of electrochemistry but does also involve the actvity of living things such as bacteria, it may seem too ambitious a target to be able to define a predicatble model based on mathematics. Fuzzy logic and calculations have the capability for this purpose and in this chapter we present one example of application fuzzt logic to describe/predict MIC.

Keywords MIC models · Fuzzy logic and calculations · Carbon steel-SRB

10.1 Introduction

Modelling in itself is an important issue. When we look at the four principles of "Corrosion knowledge Management" (Chap. 3, "Non-technical Mitigation of Corrosion: Corrosion Knowledge Management), we see that modelling is one of these principles.

But why can modelling be so important? If we define modelling as an imitation of reality, it becomes evident that when we cannot have full access to describe a reality, we need to make "something" that will resemble it "to some extent". This "something" is the model itself and the "to some extent" is another way of saying that all models do suffer from intrinsic drawback of not being completely the reality itself.

Use of models is necessary for us to be able to not only better understand the present state of a system but also to predict how it may behave in the future. This chapter will briefly focus on the application of fuzzy logic as a powerful tool to construct mathematical models of MIC.

10.2 MIC Models

When it comes to MIC, two types of modelling can be recognised:

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1. Bacteria-Specific Models
    1.1 "Melchers" Model
    1.2 "Gu" Model
    1.3 Maxwell-Pots Model
2. Process-Specific Models
    2.1 "Linear microbial Corrosion rate" model
    2.2 Checworks Predictive Model (CW)
    2.3 Union Electric Callaway MIC index (Ue)
    2.4 Lutey/Stein MIC index (L/S)
    2.5 MIC risk factor model
    2.6 Javaherdashti MIC risk model

We have explained about these models elsewhere (Javaherdashti et al. 2013) and the references are given there. Of these models, some are not mathematical at all, namely "Melchers" or "Gu" model. But models such as those given as "Process-Specific Models" have a majority of mathematical models, as the names themselves can explain for them. The examples of these models can be further extended, for example the mathematical model (Ahammad et al. 2011), proposed by Ziauddin Ahammad et al. that describes the interactive action of SRB and methanogens can be classified as a bacteria-specific model whereas the mode proposed by Salek et al. (2011) is more a process-specific model that elucidates the corrosive effect of biofilm and its corrosion accelerating effect. However, all these models are based on simple maths applied into a framework of microbiology–electrochemistry. Otherwise, all of these models have two common features:

1. They rely on a chemical–microbiological platform,
2. They have conventional mathematics in the sense that conditions for the model to be true either exist or not. In other words, parameters of the model are assumed to be "static" not 'dynamic" with time.

However, natural systems are not static, they change in time and the best example for that is the dynamic nature of biofilm construction and deconstruction cycle. We need mathematics that will take into consideration the "grey" nature of MIC processes without assuming it totally "black" or "white".

The best means to achieve a model that is studying the impact of varying factors in a given parameter is fuzzy calculations/logic. There are millions of documents, including papers, books, conference papers, etc. written and is still being written on the subject of fuzzy logics and fuzzy calculations and we have used them in many of our previous publications (Javaherdashti et al. 2012, 2004, 2000a 2000b). We will briefly explain the general guidelines that may be used to apply fuzzy logics and calculations for MIC considerations.

10.3 Fuzzy Calculations

The very nature of processes involved in MIC dictates that they are not of the type we could have otherwise called as "binary" in the sense being totally false (having a value of "0") or totally true (a value of "1"). In fact, when one looks at the physical as well as chemical properties of both the corrosive environment and the vulnerable material in the context of microbial corrosion, one cannot help but think of an artistic work by "Jackson Pollock": on the surface, chaotic but deep down, of its own order.

More or less the same "fuzzy-ness" is ruling the material–environment mutual relationship (See Fig. 5.1, in Chap. 5 "How Does a System Become Vulnerable to MIC?").

How fuzzy logic and calculations may work in relation to MIC? In fact it is no different from any other applications of fuzzy logic: you have a set of parameters (parameters of interest) that you want to know how close they can be to the members of another set of parameters (target parameters). In fact, you try to find a "ranking function" that would tell you how close the parameters of interest will be to the target parameters. The "ranking function" may alternatively be called as the "membership function", Fig. 10.1.

The way we can apply fuzzy logic/calculations into any MIC problem can be described in the same way that has been conceptually shown in Fig. 10.1: we can define a set of parameters and then define a membership function (F, in Fig. 10.1) so that it will measure how close (that is, with what probability) the set of interest and its elements can be matched with the target set elements. More details of basic concepts of fuzzy logic are given in many publications, including one of our works (Javaherdashti 2000b).

Below we will give an example of how fuzzy logic can be applied in dealing with engineering problems with a background in microbial corrosion.

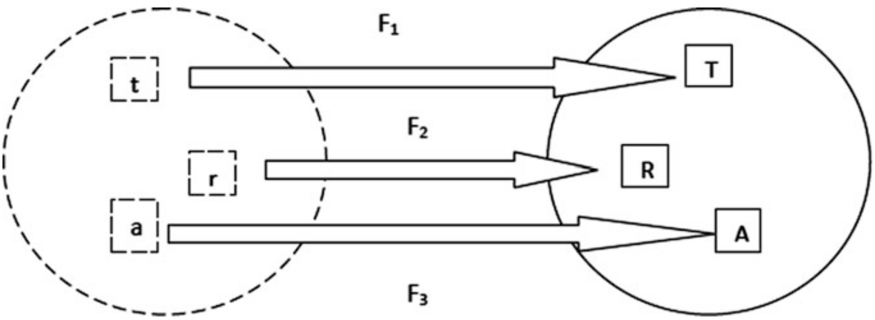

Fig. 10.1 Between two "interest" and "target" sets, three parameters are linked. Each "F" shows how close a member of the interest parameters set (*dashed line*) can be matched with its corresponding element in the target set (*solid line*)

10.4 Fuzzy Modelling of Microbial and Non-microbial Corrosion of Carbon Steel in a Post-cracked Stage in Reinforced Concrete Structures by Their Open Circuit Potential Patterns

An essential component of Reinforced Concrete (RC), steel, has been reported to have a global production magnitude of 5.8×10^8 ton/year where about 10 % of that goes to RC. Among all causes of progressive deterioration and corrosion, it has been observed that biodeterioration of structural materials may contribute significantly to the continued loss of capacity of some structures located in aggressive environments; for example, in sewer pipes, sulphur-oxidising bacteria can contribute to corrosion rates of up to 1 cm/year. Microbial corrosion of steels and mainly carbon steels which are the metallic phase of any RC structure was a known phenomenon since early 1930s (Ribas Silva and Pinheiro 2007) Sulphate-reducing bacteria (SRB) are known for their corrosive impact on almost all engineering materials, metallic or non-metallic and especially concrete structures, probably through their association with other micro-organisms such as sulphur-oxidising bacteria. There is tremendous amount of research about microbial corrosion in general and SRB in particular. When RC concrete structures are cracked and the steel rebar is exposed to the surrounding environment, SRB can be increased inside the bulk of the concrete composite and thus enhance the corrosion of the rebar. In the context of this section of our book, we will be exclusively looking at the corrosion of the steel rebar, mainly by sulphate-reducing bacteria (SRB). The obvious reason is that when the steel phase in an RC structure fails, the whole integrity of the structure will be jeopardised. In addition to that, as the interaction between the bacteria and the material is of critical importance and very complicated, fuzzy logic is used to model this relationship. The significance of fuzzy logic in mathematical modelling of many corrosion-related complex issues is a known matter (Najjaran et al. 2004; Moura et al. 2008).

10.4.1 Basic Concepts

10.4.1.1 The Main Assumption of the Model

The initiation time of reinforcement corrosion depends highly on the diffusion coefficient and on the critical chloride ion threshold, which is a property of the material. Apart from biodeterioration, diffusion increases with water–cement ratio and temperature. The corrosion of reinforcement results in an expansion of corrosion products, which exceeds the tensile strength of concrete, causing cracking. Figure 10.2 illustrates Tuutti's model where the process of corrosion-induced cracking is divided into two stages: (1) crack initiation and (2) crack propagation.

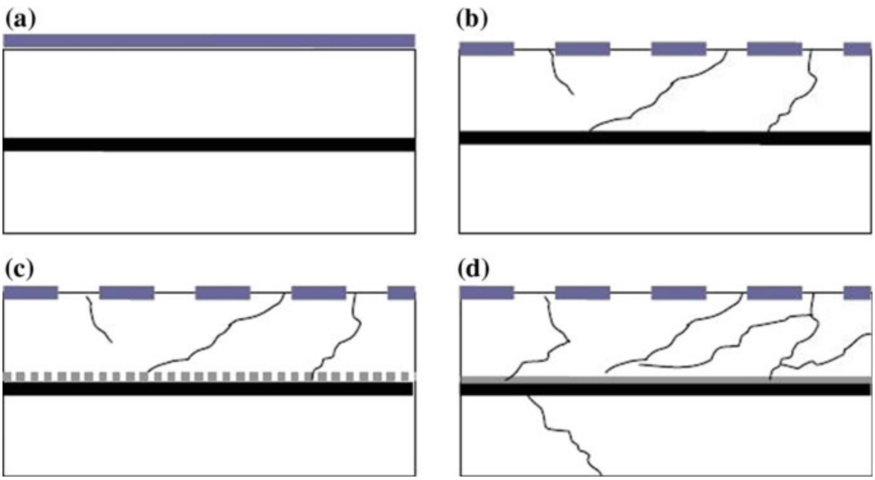

Fig. 10.2 Schematic presentation of Tuutti's model for crack initiation and propagation in RC structures

Figure 10.2 schematically shows a possible scenario of reinforced concrete structures: due to high pH of the concrete surface, the structure is sound and without crack (A) but during course of time, due to some "external factors" the outer surface of the concrete becomes conditioned as to allow cracks to develop internally (B). As the cracks develop, water ingress from outside can find its way deep into the reinforced metallic phase (C). Under these circumstances rust is developed. The developed corrosion products (rust) in physical terms will need more space that cannot be accommodated by the gap between the metallic phase and the concrete around it. The end result is that due to the internal tensile stresses thus produced, the non-metallic phase fails and cracks, thus allowing more water ingress through increasing the number of capillaries and cracks.

Crack initiation is defined by the time for which cracks of a certain width are formed. The value for the limiting crack width at the end of the crack propagation phase depends on the limit state considered. Sakai et al. (1995) defined the limit crack width as 0.3–0.4 mm for durability limit states and ACI-209 (ACI 1978) suggests a value of 0.8 mm for serviceability (aesthetics) requirements.

Main assumption of the model is that the concrete has already been cracked so that water (and micro-organism) ingress is already taking place. The justification for this fundamental assumption is that when the concrete is cracked, some organism's ingress through cracks generating tensile stresses that deteriorate the concrete by increasing the crack size and concrete porosity. It must be noted that the water absorbed into the concrete via cracks not only acts as a highly conductive electrolyte to let electrochemical process of corrosion take place, but it can also act as a good habitat for living micro-organisms that may corrode the RC structure very rapidly. The combined action of micro-organisms and the expansive pressures from steel oxidation increase the concrete cracking rate, spalling and delamination. The significance of this assumption is that the model is confined to stages where the concrete "sheath" around the carbon steel rebar is no longer functional in inducing alkalinity and thus passivation due to crack initiation and water ingress into the concrete.

10.4.2 Environment Versus Material

When it comes to corrosion, two scenarios can be suggested:

(a) Suitable Environment
(b) Susceptible Material.

A suitable environment can be defined as an environment in which corrosion is favoured. A good example of such a suitable environment is seawater (synthetic or natural).

When defined as per microbial corrosion, a suitable environment is an environment in which "biofilm" formation is favoured. Biofilms are matrix-enclosed bacterial population's adherent to each other and/or to surfaces or interfaces (Costerton et al. 1995) and they are the main cause of inducing corrosion. Alternatively, such an environment can also be called as a "biotic" environment. Examples of such suitable biotic environments are natural environments such as seawater or artificial environments such as laboratory-made broths where necessary nutrients for growing micro-organisms are made up. The abiotic environments, on the other hand, are also the control environment that mimics the biotic environments except having micro-organisms so that only the contribution of the micro-organisms will be measured by the biotic environment. Susceptible material is the one which is prone to undergo corrosion and in case of MIC, a materials on which biofilm formation can be developed. (for example, carbon steel). It will be the combination of these two parameters that will increase the likelihood of corrosion and MIC. In other words, there can be three probabilities (The underlined phrases are fuzzy concepts):

Probability (1) likelihood of corrosion is <u>relatively high</u> if both suitable environment and susceptible material exit, such as carbon steel in seawater,

Probability (2) likelihood of corrosion is <u>relatively low</u> if either suitable environment or susceptible material exits, such as stainless steel in seawater,

Probability (3) likelihood of corrosion is <u>too low</u> if neither suitable environment nor susceptible material exits, such as titanium alloy in an alkaline environment

Obviously, the above three probabilities will still hold even if we replace "corrosion" with "microbial corrosion".

10.4.3 Algorithm and Methodology

For the same susceptible material (carbon steel), three sets are defined as in Eq. (10.1) for two suitable environments, biotic environment (with SRB) and abiotic environment (synthetic seawater):

$$G = \{G_j\}, \quad j = 1, 2, 3, N \tag{10.1}$$

$$\begin{aligned} S &= \{S_i\}, \quad i = 1, 2, 3, M \\ A &= \{A(i)\}, \quad i = 1, 2, 3, M \end{aligned}$$

The set G measures all practically achievable universal properties (mechanical, physical and chemical parameters) of carbon steel in biotic and abiotic environments. Among these parameters are the alloying elements, mechanical properties, crystal structure, electrochemical properties and the like.

The set S measures the required ranges of the above mentioned universal properties of carbon steel in biotic and abiotic environments favouring both non-microbial and microbial corrosion.

The set A, on the other hand, measures the fuzzy probability of each member of the sets G to become a member of the set S. In other words, A would measure the fuzzy possibility of risk of corrosion (both MIC and non-microbial corrosion) within the given universal parameters. Therefore, a membership function $F_{A(i)}$ measures the fuzzy likelihood of a member of G (such as G_i) to become a corresponding member of S (such as $S_{i.}$). Our aim is to find out a general algorithm that would allow define A.

The condition of using the same susceptible material (carbon steel) in both suitable environments emphasizes the probability (1) where likelihood of corrosion will be relatively high.

Fuzzy membership functions for each set are defined to arrive at composite function of membership functions. By defining the composite functions fuzzy rules to characterise the environment and its important parameters are defined.

A fuzzy method known as "generalisation of compositional rule of inference" is utilised in this study. In this method, a fuzzy rule is transformed into a general form of multi antecedents (inputs) and consequents (outputs). Also *Kosko decomposition method* for decomposing a fuzzy rule and *Mamdani minimum fuzzy implication* will be used.

By utilising *Mamdani minimum fuzzy implication*, the minimum value of membership functions of the given fuzzy sets is calculated. Then, by maximum-minimum technique, first the minimum values of membership functions are calculated. After that, among the selected minimum values, the maximum value is picked up. If in any case, the membership functions of some elements are equal, one of the functions is chosen.

10.4.4 Fuzzy Model

10.4.4.1 Universal Properties of Carbon Steel in Biotic Environment

Assume that there are various U universal features that can favour (microbial) corrosion of carbon steel and not necessarily be related to each other (such as the surface roughness of the metal and the metal's alloying elements). We may assume that for each G_j, there is a feature such as K so that $K = 1, 2, 3,\ldots, U$.

When G_j is considered for a special universal feature such as K, it may also be assumed that the parameter will be a random variable such as $x(j, K)$ that obeys a normal distribution function. For any factor that can help corrosion, and especially MIC, and is expressed as S_i, one may assume that $m(i, K)$ and $M(i, K)$ are, respectively, the permissible minimum and maximum thresholds for the universal feature K to be expressed by S_i.

This will be translated as Eq. (10.2) in terms of fuzzy probability function:

$$F_{A(i,K)}(Gj) = \mathrm{Prob}(m(i, K) \leq x(j, K) \leq M(i, K)) \quad (10.2)$$

where $K = 1, 2, 3,\ldots, U$, $i = 1, 2, 3,\ldots, M$, $j = 1, 2, 3,\ldots, N$

Equation (10.2), in terms of a membership function $F_{A(i,k)}(G_j)$, defines the fuzzy likelihood of an existing universal feature such as K from the range of universal features G_j to become an element of S_i. Roughness is, for example, an important feature that can promote MIC by "harbouring" bacteria. Equation (10.2) can then be used to calculate the best membership function value that will allow the roughness of the surface to make it vulnerable and receptive of biofilm formation and thus undergo MIC. Likewise, we can also think of electrochemical features of carbon steel as measured by open circuit potential-that essentially measures corrosion potential-in the biotic environment.

10.4.4.2 Universal Properties of Carbon Steel in Biotic Environment

Assume that there are various V universal features that can favour non-microbial corrosion of carbon steel and not necessarily be related to each other for instance the impact of alloying elements such as decreasing concentration of chromium in grain boundaries due to factors such as carbide formation that will make it possible for the micro-organisms to prefer to colonise the grain boundaries.

We may assume that for each G_j there is a chemical feature such as L so that $L = 1, 2, 3, \ldots, V$.

When G_j is considered for a universal feature such as L, it may also be assumed that the parameter will be a random variable such as $x(j, L)$ that obeys a normal distribution function. For any factor, expressed as S_i, that can help biofilm formation and induce microbial corrosion, one may assume that $m(i, L)$ and $M(i, L)$ are, respectively, the permissible minimum and maximum thresholds for the universal feature L to be expressed by S_i.

Therefore the related membership function, in terms of fuzzy probability function, can be shown as Eq. (10.3):

$$F_{A(i,L)}(G_j) = \text{Prob}(m(i,L) \leq x(j,L) \leq M(i,L)) \quad (10.3)$$

where $L = 1, 2, 3, \ldots, V$, $i = 1, 2, 3, \ldots, M$, $j = 1, 2, 3, \ldots, N$

Equation (10.3), in terms of a membership function $F_{A(i,L)}(G_j)$, defines the fuzzy likelihood of an existing feature such as L from the range of the universal features G_j to become an element of S_i, suitable for non-microbial corrosion of carbon steel.

10.4.5 Fuzzy Composite Functions

Equations (10.2) and (10.3) define how "close" the value of a given universal feature of carbon steel in biotic and abiotic environments can be to the range of risky values to become eligible for MIC and non-microbial corrosion. Now these membership functions need to be defined as a single function in accordance with fuzzy functions. In other words, a composite function $\mathrm{F_{A(i)}}$ must be defined as a function of both $F_{A(i,K)}(G_j)$ and $F_{A(i,L)}(G_j)$.

A composite function for each $G_j \in G$ can be defined for the universal features of the carbon steel in biotic and abiotic environments, respectively, as Eqs. (10.4) and (10.5):

$$F_{K(i)}(G_j) = \frac{\text{Max}}{K}\{F_{A(i,K)}G_j\} \quad (10.4)$$

$$F_{L(i)}(G_j) = \frac{\text{Max}}{L}\{F_{A(i,L)}G_j\} \quad (10.5)$$

The Eqs. (10.4) and (10.5) explain that among the membership functions for each set, the maximum values must be picked up. The fuzzy subset $A_{K(i)}$ (a member of G) defined by the membership function $F_{K(i)}(G_j)$ shows that with what (fuzzy) probability a certain range of the universal features of the biotic environment can have the conditions that will render carbon steel prone to microbial corrosion, as indicated by S_i. Likewise, the fuzzy subset $A_{L(i)}$ (a member of G) defined by the membership function $F_{L(i)}(G_j)$ shows that with what (fuzzy) probability a certain range of the universal features of the abiotic environment can have the conditions that will render carbon steel prone to non-microbial corrosion, indicated by S_i. It must be noted that the values of both $F_{K(i)}(G_j)$ and $F_{L(i)}(G_j)$ can be assumed to be not arbitrary variables which are independent of each other.

Equation (10.6) defines the fuzzy membership function, $F_{A(i)}$, for the fuzzy subset $A(i)$ (belonging to A) in such a way that it can measure the fuzzy possibility, S_i (belonging to S) of a combined range of universal features G_j (belonging to G) for becoming vulnerable to the value necessary for MIC and non-microbial corrosion.

Assuming $G_j \in G$:

$$F_{A(i)}G = \begin{cases} \text{If } \max\left\{F_{K(i)}G_j,\ F_{L(i)}G_j\right\} = 0. & \text{Then } 0 \\ \text{If } \max\left\{F_{K(i)}G_j,\ F_{L(i)}G_j\right\} = 0. & \text{Then } \gamma_{\text{Bio}}F_{K(i)}G_j + \gamma_{\text{Abio}}F_{L(i)}G_j \end{cases} \tag{10.6}$$

where $\gamma_{\text{Bio}} + \gamma_{\text{Abio}} = 1$, $\gamma_{\text{Bio}}, \gamma_{\text{Abio}} \leq 1$.

Equation (10.6) addresses the probability for carbon steel in biotic environment to microbial corrosion (MIC) and in abiotic environment to non-microbial corrosion in terms of coefficients (weights) γ_{Bio} and γ_{Abio}.

Obviously, as the tests will be done in two separate environments, each γ value must be taken for that particular environment. Therefore, when the biotic environment is being tested, $\gamma_{\text{Abio}} = 0$ and likewise, when the abiotic environments is being tested, $\gamma_{\text{Bio}} = 0$. When the γ values for each environment is determined, the comparing them with each other can result in three fuzzy possibilities for a susceptible material in two suitable environments:

Fuzzy Possibility 1 $\gamma_{\text{Bio}} > \gamma_{\text{Abio}}$ meaning that carbon steel in biotic environment is more susceptible(less resistant) to corrosion in comparison with abiotic environment. Therefore MIC of carbon steel is more likely,

Fuzzy Possibility 2 $\gamma_{\text{Bio}} < \gamma_{\text{Abio}}$ meaning that carbon steel in biotic environment is less susceptible (more resistant) to corrosion in comparison with abiotic environment. Therefore MIC of carbon steel is less likely,

Fuzzy Possibility 3 $\gamma_{\text{Bio}} = \gamma_{\text{Abio}}$ meaning that there will be no preference in the corrosion behaviour of carbon steel in either biotic or abiotic environments

γ can be arbitrarily defined as a dimensionless value, $P_{\text{Mean}}/P_{\text{Max}}$, Eq. (10.7):

$$\gamma = [P_{\text{Max}}/P_{\text{Mean}}] \tag{10.7}$$

Where P_{Mean} is the average value of corrosion potential (in mV) of carbon steel in a given environment and P_{Max} is maximum value of corrosion potential (in mV) of carbon steel in that given environment.

10.4.6 Validation

10.4.6.1 Experimentation

Susceptible Material

As the susceptible material carbon steel with the following universal features were selected.

Chemical Composition

The chemical composition of the carbon steel samples that were used for the experimental purposes in this study is given in Table 10.1:

Suitable Environments

Abiotic Environment

As mentioned earlier, in all types of experiments related to microbial corrosion, a control environment is used that in essence, in its chemistry it is similar to the main biotic environment except the target micro-organism(s). Therefore, synthetic seawater test medium was used as abiotic medium. The synthetic seawater used in these series of experiments was prepared as 35 g/l NaCl solution (3.5 % NaCl solution wt%/wt%) whose pH had been adjusted to 8.20 by using 0.1 N NaOH solution.

Biotic Environment

The main media supporting the growth of the corrosion-related bacteria contained 35 g/l of NaCl added to the ingredients listed in Table 10.2 and the pH of the medium before autoclaving was adjusted to 8.20 using 0.1 N NaOH solution. After autoclaving the measured pH was ≥7.5.

Bacterial Cultures

The sulphate-reducing axenic (i.e. single type) culture was isolated from a sub-culture taken from a muddy marine sediment taken from a depth of 14 m. The growth was

Table 10.1 Chemical composition of the carbon steel (as received from the manufacturer)

Element	C	Cu	Al	Nb	V	Ti	P	Mn	Si	S	Cr	Mo	Ni
wt%	0.25	0.50	0.15	0.01	0.03	0.04	0.05	1.6	0.4	0.04	0.3	0.1	0.5

Table 10.2 Composition of postgate B medium

Chemical	g/l of distilled water
K_2HPO_4	0.5
NH_4Cl	1.0
$CaSO_4 \cdot 2H_2O$	1.3
$MgSO_4 \cdot 7H_2O$	2.0
Lactic acid (88 %)	2.7
Yeast extract	5.0

characterised by both hydrogen sulphide odour and blackening of the test tube. The bacterium was determined by its morphology to be a *Desulfovibrio* sp.

Test Procedure

To evaluate the performance of carbon steel in biotic and abiotic environments, it was decided to perform open circuit potential (OCP) tests on carbon steel in both environments. OCP is a "safe" electrochemical method, contrary to a majority of other methods (See Chap. 6, Sect. 6.3.3).

To determine OCP of the steel in the biotic and abiotic environments, a piece of the steel ($\sim 1 \times 1$ cm^2) was placed in resin with a wire spot welded at its back. To protect the wire from the media, it was placed within a glass tube. The potential change of the electrode was recorded with respect to a non-leaking saturated Ag/AgCl reference electrode in a flask with an approximate volume of $\sim$700 ml via a data taker. The working electrode and Ag/AgCl reference electrodes were connected to a voltmeter that recorded potential changes each 10 min and feeds the data into a data taker. Before each test, conductivity of the working electrode was checked by a voltmeter. Both the steel electrode and the reference electrode were sterilised by autoclaving. All metallic and glass components of the bioreactor were autoclaved at 121 °C for 15 min. Under sterile flow of air, the bioreactor was assembled and 1 ml of the isolated SRB culture was inoculated. Before inoculation, the inoculum was checked to be assured about viability of the micro-organisms. Open circuit potential under anaerobic conditions (for SRB) was measured by filling the OCP test flask with the inoculated medium almost intact (to drive away the air) and then placing a layer of sterile paraffin oil on the surface to prevent the entrance of air.

10.4.7 Results and Discussion

Figure 10.3 shows the OCP of carbon steel in biotic(SRB culture) and abiotic (synthetic seawater) environments. It is seen from Fig. 10.3 is that the carbon steel in abiotic environment shows a rather smooth pattern with a potential around −500 mV versus Ag/AgCl reference (RE) electrode. Figure 10.2 also illustrates how OCP of the carbon steel is changing in SRB-containing biotic environment. As

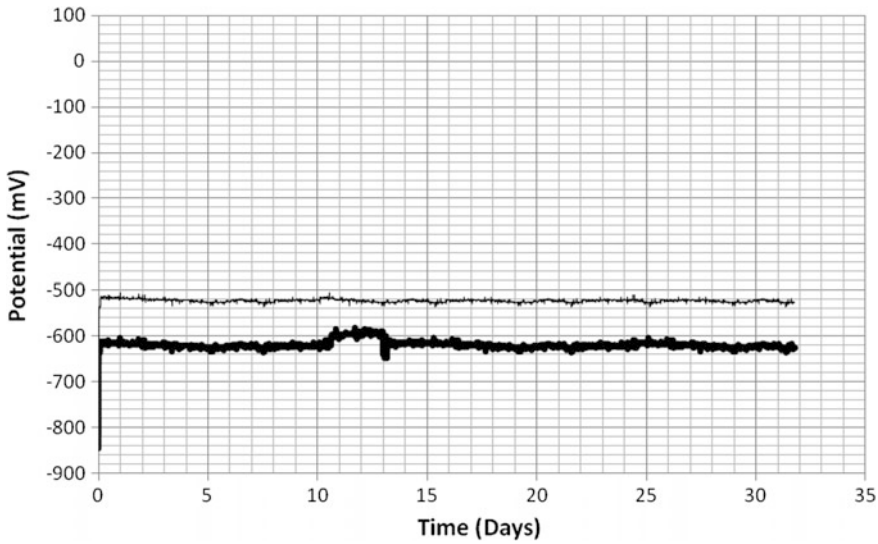

Fig. 10.3 Open circuit potential of carbon steel in SRB-containing biotic (*thin line*) and abiotic (*thick line*) synthetic seawater environments

it appears, fluctuations in the potential show "noble" peaks as high as −580 mV to "active" peaks of about −840 mV in the biotic environment. The OCP remains active at around −600 mV for about 3 days and then rises up to potentials around −580 mV. This pattern of decreasing and increasing the potential is repeated afterwards where after about 21 days, the potential decreases with repeating the same fluctuating pattern of potentials.

The OCP pattern, from time to time, manifests itself in the form of "jumps", especially in the biotic environment. While at this stage nothing can be said about exact mechanism(s) that may be involved in producing such serrated pattern for OCP data, these fluctuations of potential are a well-known yet not fully explained phenomenon when OCP is used in microbial environments. Therefore, a possibility for continuous build-up and breakdown of protective films, such as ferric oxide film or in biotic environments, a biofilm formation–destruction cycle, should not be ruled out. The fluctuations of potential can be interpreted as mixed effect of bacterial activity and purely chemical effects of some compounds that for example in the case of SRB, could be sulphide. Table 10.3 summarises the maximum and average (mean) values of potentials in biotic and abiotic environments.

However, the cause of these fluctuations in the observed OCP potentials is of secondary importance. For the validation of the fuzzy model we need to know the γ values. Based on the above potentials, the γ values for biotic (γ_{Bio}) and for abiotic environments (γ_{Abio}), respectively, will be as follows (Eqs. (10.8) and (10.9)):

Table 10.3 OCP (mV) for the susceptible material (carbon steel) in the suitable environments containing SRB (biotic environment) and synthetic sea water(abiotic environment)

Environment	Maximum potential (mV)	Mean potential (mV)
Biotic	−582	−619.41
Abiotic	−504	−522.30

$$\gamma_{Bio} = 0.94 \quad (10.8)$$

$$\gamma_{Abio} = 0.96 \quad (10.9)$$

As seen from Eqs. (10.8) and (10.9), it is the fuzzy possibility 3($\gamma_{Bio} = \gamma_{Abio}$) that **is** applicable. In other words, there is no preference in the corrosion behaviour of carbon steel in both biotic and abiotic environments. This suggests that under these conditions, carbon steel can be corroded with almost the same possibility of being exposed to sulphate-reducing bacteria or synthetic seawater, at least under the testing conditions.

Perhaps an immediate practical outcome of these results is that the existence and activity of SRB could be as much important as the effect of chlorides. This will mean that the deterioration of RC structure must be monitored very carefully not to cross to post-crack initiation stage and let the structure crack so that the bulk of the structure and the steel rebar are exposed to the corrosive environments, either biotic or abiotic. Therefore,

- Fuzzy logic has the capability of predicting the behaviour of steel rebar inside RC concrete structures,
- Biotic environment containing SRB will have the same effect on the corrosion of carbon steel as abiotic environments containing chlorides, implying that the severity of corrosion of carbon steel can in biotic environments be as severe as abiotic environments.

10.5 Conclusions

Fuzzy logic and Fuzzy calculations can be a powerful tool to tackle MIC modelling problems. The main reason for that is that processes involved in any MIC case are too complicated to be explained by “conventional” methods only. Mathematical modelling is, and must always be, an integral part of any MIC research to allow to not only understand the current situation of a system but predict how it will look like in the future should the conditions vary within certain framework.

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