

# Corrosion of steel in concrete structures

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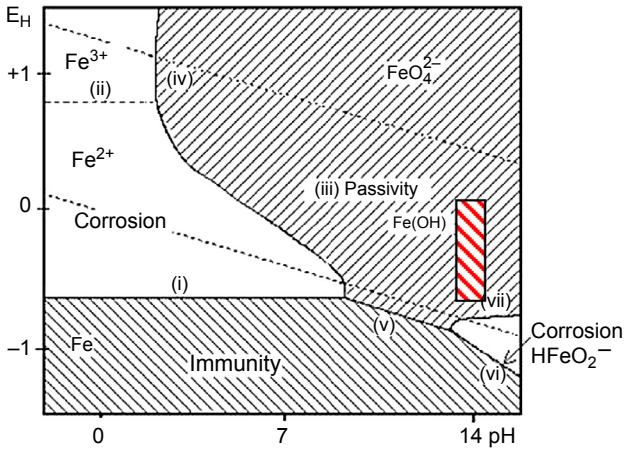
## 2.1 Introduction

The low cost of steel-reinforced concrete and the ready availability of raw materials with which it is formed make it the most widely used structural material available. The durability of structures made from steel-reinforced concrete is related to its ability to impede or greatly reduce the rate of moisture transport or the ingress of aggressive ions. However, because many existing concrete structures are under constant degradation from aggressive environments, they suffer from durability issues, particularly corrosion of the steel bars within such structures. This corrosion in turn has created a multi-billion-dollar infrastructure deficit. Unfortunately, sequestration, with its adverse impact on discretionary revenues, has alarmingly reduced the revenues necessary for repairing US infrastructures, which become more degraded by the day (Thompson, 2013). Currently, one in nine of the nation's bridges is deemed structurally deficient (ASCE, 2013). Indeed, the FHWA report on corrosion protection of concrete bridges estimated in 2002 that the average direct cost of corrosion for highway bridges was \$8.3 billion per year (Yunovich et al., 2001). Considering inflation, this cost is much higher in 2016. Given the current state of US infrastructure, there is a critical need to undertake corrosion research for a nation in desperate need of such services. The corrosion of reinforcing steel in concrete is a serious problem from the perspective of both safety and economy and can directly affect the sustainability of the infrastructure.

## 2.2 Passivation/depassivation

Concrete provides physical corrosion resistance to steel reinforcement by acting as a barrier, and chemical corrosion resistance as a result of its high pH. Concrete that is not exposed to any external influences usually exhibits a pH between 12.5 and 13.5 (Hansson, 1984). As shown in the Pourbaix diagram (Figure 2.1), which defines the range of electrochemical potential and pH for the Fe-H<sub>2</sub>O system in an alkaline environment, at potentials and pHs normally found within the concrete, a protective passive layer forms on the surface of steel.

It is believed that this layer is an ultrathin (<10 nm) protective oxide or hydroxide film that decreases the dissolution rate of steel to negligible levels (Zakroczymski



**Figure 2.1** Pourbaix diagram for Fe-H<sub>2</sub>O at 25 °C (Pourbaix, 1974). Hatch area shows the pH and potential region of steel in concrete.

et al., 1985; Montemor et al., 1998; Carnot et al., 2002). However, the partial or complete loss of the passive layer, known as depassivation, leads to the active corrosion of steel bars. The corrosive products of iron are expansive, and their formation can cause cracking and further deterioration in concrete.

Limited research has been carried out on the formation and breakdown of the passive layer. It has been observed that the oxidation state of the iron passive layer varies across the layer. It is assumed that the outer layer that is mainly composed of  $Fe^{3+}$  rich oxides and hydroxides is nonprotective, and that the inner oxide layer adjacent to the steel that is rich in  $Fe^{2+}$  is protective (Ghods et al., 2009). It is also known that the  $Fe^{3+}/Fe^{2+}$  ratio increases in the presence of chloride ions (Gunay et al., in press). It was hypothesized that when chloride ions diffuse through the nonprotective outer layer and come into contact with the inner layer, they convert some  $Fe^{2+}$  oxides/hydroxides to  $Fe^{3+}$  oxides/hydroxides that reduce the protective nature of the inner layer (Ghods et al., 2009; Gunay et al., in press).

Chloride ions that come mostly from deicing salts or seawater, and carbon dioxide from the atmosphere, are two major factors that can break the passive film on the surface of steel and initiate corrosion. Insufficient oxygen to preserve the passive film, galvanic cell formation from the contact of different metals, and stray currents are the other factors that may cause active corrosion in reinforced-steel structures.

### 2.2.1 Semiconductive behavior of passive layers

Due to the nature of passive layers on metals, they usually exhibit the electrochemical properties of a semiconductor (Morrison, 1981; Bard and Mirkin, 2001). The electronic structure of these solids is usually discussed in terms of energy bands. The highest occupied and lowest unoccupied levels, called the valence band and

the conduction band, respectively, are of interest. The gap between these bands determines the properties of the material. Conductivity of a solid-state material is achieved by occupancy of the conduction band. For semiconductors, the band gap ( $E_B$ ) is not as large, and electrons can be moved into the conduction band (Bard and Mirkin, 2001). The movement of electrons leaves a positively charged vacancy in the electrical valence, which is referred to as a hole (Morrison, 1981). Holes are considered to be mobile and to cause conduction. Doping, another method for generating charge carriers (using electrons or holes) within a semiconductor, involves the addition of a different element, dopant, into the semiconductor (Morrison, 1981). Doped semiconductors, in which the majority of charge carriers are electrons, are n-type semiconductors, whereas those in which holes are the majority of charge carriers are p-type semiconductors. The generation of charge carriers requires the presence of dopants. The dopants must be able to: give off electrons to the conduction band, in which case they are called donors (they provide free electrons to n-type semiconductors); or give off holes to the valence band, in which case they are called acceptors (they provide free holes to p-type semiconductors). When a semiconductor contacts an electrolyte, electrical charges are transferred between the semiconductor phase and the solution phase. The electrochemical potential of the solution is determined by the redox potential of the electrolyte solution (Uhlig, 1985), and the redox potential of the semiconductor is determined by the Fermi level, which is defined as the energy level at which the probability of occupation by an electron is 50% (Morrison, 1981; Bard and Mirkin, 2001). If the redox potential of the solution and the Fermi level do not lie at the same energy level, a movement of charge between the semiconductor and the solution is required in order to equilibrate the two phases. For a semiconductor, the excess charge extends into the electrode for a significant distance (Morrison, 1981). This region is referred to as the space charge region and is composed of two double layers: the interfacial (electrode/electrolyte) double layer and the space charge double layer ( $C_{SC}$ ). At a certain potential, the Fermi level lies at the same energy level as the solution redox potential; there is no net transfer of charge, hence there is no band bending. This potential is known as the flat-band potential,  $E_{fb}$ . The charge distribution at the interface between a semiconductor and an electrolyte is often determined by measuring the capacitance of the  $C_{SC}$  as a function of the electrode potential ( $E$ ). When the space charge double layer serves as a depletion layer, the relation of the capacitance and the potential follows the Mott–Schottky equation (Morrison, 1981; Sukhotin et al., 1989):

$$\left\{ \frac{1}{C_{sc}^2} = \frac{2}{\epsilon\epsilon_0qN} \left( E - E_{fb} - \frac{kT}{q} \right) \right\} \quad (2.1)$$

The Mott–Schottky relationship ( $1/C_{sc}^2$  vs  $E$  plot) expresses the potential dependence of the  $C_{SC}$  of a semiconductor electrode under depletion types, where  $N$  represents the donor ( $N_D$ ) or acceptor density ( $N_A$ ),  $\epsilon$  is the dielectric constant of the passive layer,  $\epsilon_0$  is the vacuum permittivity,  $q$  is electron charge of an electron,  $E_{fb}$  is the

flat-band potential,  $k$  is the Boltzmann constant, and  $T$  is the absolute temperature.  $N_D$  and  $N_A$  can be determined from the slope of the experimental  $1/C_{sc}^2$  vs  $E$  plots, while  $E_{fb}$  comes from the extrapolation for  $1/C_{sc}^2 = 0$ .

The characteristics and roles of passive layers on Fe base metal and alloys have been one of the most important subjects of study in corrosion science. Since the passive layer on the surface of steel could be interpreted in terms of a semiconductive layer (Paola et al., 1986; Sunseri et al., 1987; Paola, 1989; Simoes et al., 1990; Schmuki and Böhni, 1992; Belo et al., 1999), its electronic properties play an important role in the corrosion resistance of the steel. Mott–Schottky analysis has been successfully used to investigate the semiconductive properties of passive layers on metals, specifically in obtaining the type of the semiconductor, donor density ( $N$ ), and the flat-band potential ( $E_{fb}$ ) (Harrison and Williams, 1986; Burleigh and Latanision, 1987; Paola, 1989; Simoes et al., 1990; Paola and Shukla, 1991; Schmuki and Böhni, 1992). However, the number of studies on the semiconductive properties of the passive layer in an alkaline concrete environment is very limited. In their study of the semiconductive behavior of the passive layer of steel in chloride-free and chloride-contaminated concrete pore solutions, Zhang and Li concluded that the passive layer on a steel bar in concrete is a highly disordered n-type semiconductor (Paola and Shukla, 1991). They also found that in the presence of chloride ions, the semiconductive behavior of the passive layer changes, thus causing a decrease in corrosion resistance and a thinner passive layer on rebar. They did not, however, investigate the semiconductive properties of the passive layer under different loading types. In the examination of the semiconductive behavior of the passive layer on steel under different loading types, Zhang and Poursaee (in press) found that, irrespective of the type and magnitude of the applied load, the passive layer on rebar in a concrete simulate pore solution was a highly disordered n-type semiconductor. In all specimens tested, they observed that the presence of chloride ions increased the slope of the Mott–Schottky plots and decreased both the donor density and the space charge layer thickness. This increase in slope and decrease in donor density and charge layer thickness in turn led to a thinner passive layer, which degraded much faster and was much more vulnerable to active corrosion.

## 2.2.2 Reinforcing steel passivation time

Portland cement concrete pore solution mainly consists of saturated  $\text{Ca}(\text{OH})_2$  ( $\text{pH} = 12.6$ ), but the presence of  $\text{NaOH}$  and  $\text{KOH}$  increases the  $\text{pH}$  to more than 13 (Poursaee, 2010). In concrete structures, the steel normally has many years to develop a protective passive film over its surface before chlorides penetrate the concrete cover. This is not the case in laboratory specimens. Nevertheless, Poursaee and Hansson (2007) showed that steel bar in mortar and pore solution does need a significant amount of time for passivation. For the corrosion rate of steel in mortar to drop to a rate typically considered passive takes approximately seven days, but the corrosion rate continues to decrease slowly for a long period after that. For steel in pore solution, the corrosion rate took about three days to drop to passive levels, and again continued to decrease very slowly thereafter.

## 2.3 Chloride-induced corrosion

Chloride ions can be present in the concrete due to the use of chloride-contaminated components, the use of  $\text{CaCl}_2$  as an accelerator when mixing the concrete, or diffusion into the concrete from the outside environment (Thuresson, 1996). Use of deicing salts during the wintertime is the largest source of chlorides in Ontario, Canada.

A localized breakdown of the passive layer occurs when a sufficient amount of chlorides reach reinforcing bars, and the corrosion process is then initiated. Chlorides in concrete can be either dissolved in the pore solution (free chlorides) or chemically and physically bound to the cement hydrates and their surfaces (bound chlorides). Only the free chlorides dissolved in the pore solution are responsible for initiating the process of corrosion (Martin-Perez et al., 2000).

There are three theories about the chloride attack (ACI Committee 222, 1996):

1. Penetration of chloride ions to the oxide film on steel through pores or defects in the film is easier than penetration of other ions.
2. Chloride ions are adsorbed on the metal surface in competition with dissolved  $\text{O}_2$  or hydroxyl ions.
3. Chloride ions compete with hydroxyl ions for the ferrous ions produced by corrosion and a soluble complex of iron chloride forms that can diffuse away from the anode, destroying the protective layer of  $\text{Fe}(\text{OH})_2$  and permitting corrosion to continue.

The current approach to quantify chloride-induced rebar depassivation in concrete is in the form of defining chloride threshold values, certain critical concentrations at which the passive film is damaged and corrosion is initiated. Hausmann, in his article that was appropriately titled “Three Myths About Corrosion of Steel in Concrete” (Hausmann, 2007), identified three misconceptions (“myths”) with the current understanding of steel corrosion in concrete. The first two myths that are relevant to this project are: (1) “passivating film on steel in concrete is destroyed when high concentrations of chloride ions reach the steel surface”; and (2) “to prevent chloride-induced steel corrosion in concrete, the soluble chloride content should not exceed 0.06% of cement weight in prestressed concrete and 0.15% in reinforced concrete exposed to chlorides in service.” Although there is a general acceptance of the chloride threshold value theory qualitatively, the above-mentioned myths, and uncertainty in existing chloride threshold data (Hansson and Sørensen, 1990; Zhang, 2008; Angst et al., 2009) are clear indicators that scientists and engineers still do not have a clear understanding of why, how, and when steel bar depassivates in concrete exposed to chloride ions.

## 2.4 Carbonation-induced corrosion

When concrete is exposed to air, the calcium hydroxide reacts with water and carbon dioxide in the air:



The effect of carbonation is to reduce the pH value of the surface layer of the concrete to less than 8.3. This pH is sufficient to make the passive layer on the reinforcement rebar unstable (Allen and Forrester, 1983). The depth of carbonation increases with time, and the rate at which it advances is a function of relative humidity (RH): the penetration of the  $\text{CO}_2$  into the concrete is highest at low RH, but the reaction with the  $\text{Ca}(\text{OH})_2$  takes place in solution and is therefore highest in saturated concrete. The net result of these two factors is that carbonation is most rapid in the 50–70% RH range (Tuutti, 1980, 1982). The carbonation front penetrates the concrete at an ever-decreasing rate because of three factors. First, the gas has to penetrate further into the concrete. Second, the concrete continues to hydrate and becomes more impermeable as it ages. Finally, carbonation itself decreases permeability, both by the precipitation of the carbonate in the existing pores and because the reaction releases water, which could result in increased hydration (Hansson et al., 2007). When the carbonation front reaches the reinforcement, the passive film is no longer stable and active corrosion initiates. Unlike chloride-induced corrosion, the corrosion process is generalized and relatively homogeneous. Moreover, the corrosion products tend to be more soluble in the neutral carbonated concrete, and may diffuse to the surface as rust stains on the concrete rather than precipitating in the concrete cover and causing stresses and cracking. Corrosion rates of carbonation are lower than those of chlorides, but over a long period, the cross section of the rebar can be reduced significantly even while there is little visible damage to the concrete. Although an intermediate RH provides the highest rate of carbonation, active corrosion of any significance does not occur in that humidity range (Rosenberg et al., 1989). Consequently, the most aggressive environment for carbonation-induced corrosion is alternate semidry and wet cycles (Tuutti, 1980). Carbonation can therefore be a major factor in the durability of concrete in hot climates, where the concrete is easily dried out and periodically subjected to saturation by rainstorms. Chloride attack and carbonation can act synergistically, and are responsible for major problems in hot coastal areas. Carbonation-induced corrosion is not found to be a major problem in northern North America, where adequate concrete cover over steel is used.

#### **2.4.1 Carbonation depth measurement**

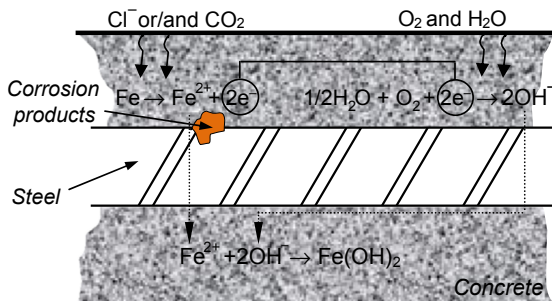
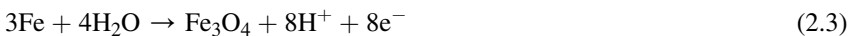
Carbonation depth is the average distance from the surface of concrete or mortar where carbon dioxide has reduced the alkalinity of the hydrated cement (NORDTEST, 1989). Depending on the concrete quality and curing condition, the carbonation depth varies. The depth of carbonation can be determined by different techniques. Microscopic observation of  $\text{CaCO}_3$ , which is the main chemical product of carbonation, is one technique that can be used for this purpose (ASTM, 2004). As mentioned before, carbonation reduces pH, and therefore examination of the internal pH of the concrete by applying pH-sensitive liquid indicators such as phenolphthalein to the freshly fractured or freshly cut surface of concrete can be used to estimate the depth of carbonation. Upon application of phenolphthalein, noncarbonated areas turn red or purple, while carbonated areas remain colorless. The maximum color change

to deep purplish-red occurs at pH of 9.8 or higher. Below 9.8, the color may be pink, and at pH of 8, colorless (Verbeck, 1995). The Rainbow Indicator<sup>®</sup> (Germann Instruments Inc., 2006) is a combination of specific chemicals that produces a range of color based on the different pH when sprayed on a freshly broken concrete surface (Campbell et al., 1991).

## 2.5 Mechanism of corrosion in reinforced concrete

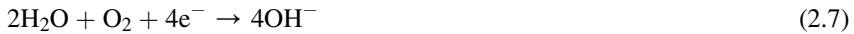
Corrosion is an electrochemical reaction that consists of anodic and cathodic half-cell reactions. Microcell corrosion is the term given to the situation where active dissolution and the corresponding cathodic half-cell reaction take place at adjacent parts of the same metal part. For a steel reinforcing bar (rebar) in concrete, this process always occurs in practice. The surface of the corroding steel can act as a mixed electrode containing both anode and cathode regions connected by the bulk steel. Macrocell corrosion can also form on a single bar exposed to different environments within the concrete or where part of the bar extends outside the concrete. In both cases, concrete pore solution functions as an electrolyte. Figure 2.2 shows a schematic illustration of corrosion in concrete-reinforcing steel.

For steel embedded in concrete, based on the pH of the concrete (electrolyte) and the presence of aggressive ions, the following would be the possible anodic reactions (Hansson, 1984; Ahmed, 2003):



**Figure 2.2** Schematic illustration of the corrosion of reinforcement steel in concrete (Ahmed, 2003).

The possible cathodic reactions depend on the availability of  $O_2$  and on the pH near the steel surface. The most likely reactions are as follows (Hansson, 1984; Ahmed, 2003):



The corrosion products occupy a greater volume than the steel itself, and this causes internal expansion and stress. The stress can destroy the concrete and expose the steel to more aggressive factors.

## 2.6 The influence of concrete parameters on rebar corrosion

Chloride ions or carbon dioxide penetrates the concrete cover depth to reach the surface of the reinforcing steel by a number of mechanisms. The surface of the concrete may be dry, allowing the dissolved chlorides or carbon dioxide to be absorbed by capillary action together with moisture through the interconnected pores in the cement paste. At deeper levels, concrete rarely dries out in the atmosphere (Hong and Hooton, 1999), so the continued penetration by aggressive ions is by diffusion through the pores, which is a much slower process than absorption.

Porosity in cement paste consists of capillary pores, gel pores, and calcium silicate hydrate (C-S-H) interlayers (Soroka, 1979). Capillary pores are the remains of originally water-containing spaces between cement particles that have not been filled up by products of hydration (Powers, 1960). They are the largest with a diameter  $>5$  nm (Mehta, 1986), and their number and interconnectivity control the ingress of chloride ions, carbon dioxide, oxygen, and moisture into concrete (Jensen et al., 1999). Gel pores and interlayer spaces are believed to be too small and disconnected to contribute to transport. Two factors that significantly influence capillary porosity in concrete are the water-to-binder (w/b) ratio (Kosmatka et al., 2002) and the use of supplementary cementing materials (Oh et al., 2002). Practically, a w/b ratio of 0.42 is required for the complete hydration of cement. However, hydration is a gradual process, and the unused mixing water is retained in the capillary pores (Aïtcin et al., 1997). Higher w/b ratios, traditionally used to give a workable mixture, increase the amount and interconnectivity of capillary porosity in the cement paste, allowing for greater diffusion. With the advent of high-range water-reducing agents, much lower w/b ratios are now possible and significantly limit the penetration of chloride ions and carbon dioxide. There are other factors that can affect the diffusion of the chloride ions and carbon dioxide (Verbeck, 1995):

- Inadequate cover provides shorter path for diffusion and is regularly associated with areas of high corrosion risk due to both carbonation and chloride ingress.
- The age of the concrete is another factor affecting the diffusion of aggressive ions. With passing time, the curing process continues and diffusion becomes harder. In addition, diffusion is a function of time, and thus its rate decreases with time.

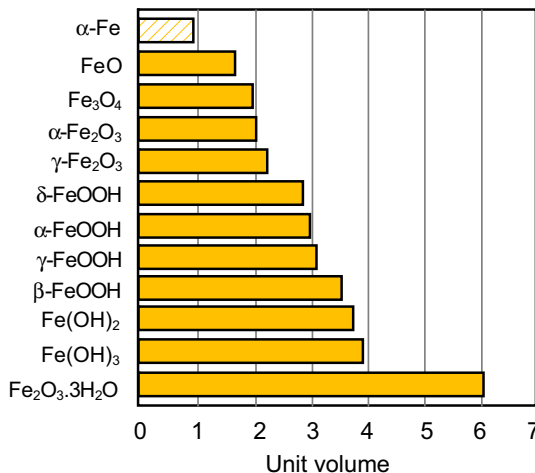


- Curing is another parameter that changes the diffusion of chloride ions and carbon dioxide into concrete (Balayssac et al., 1995; Lo and Lee, 2002). Better curing causes lower permeability, better hydration, more CH, and consequently less carbonation and chloride diffusion.
- Temperature and RH are additional factors that can affect the diffusion of aggressive species into concrete (Jones et al., 1995; Andrade et al., 1999; Khatib and Mangat, 2002; Woo-Yong et al., 2003). Diffusion is a function of temperature. For carbonation, there is a critical point that allows for the evaporation of water released by carbonation reactions, but does not result in enough drying out of the concrete to stop the reaction. RH (Gonzalez and Andrade, 1982), wind, direction of sunlight, and the type of environment (e.g., pollutant and coastal regions) are the other effective factors.

## 2.7 Corrosion products

The volume of corrosion products directly affects the proportion of concrete damage and consequently plays an important role in modeling structural performance and service life prediction. As can be seen in Figure 2.3 (Lide, 1999), different corrosion products of steel occupy different volumes.

Suda et al. (1993) detected  $\text{Fe}_3\text{O}_4$  (magnetite),  $\alpha\text{-FeOOH}$  (goethite), and  $\gamma\text{-FeOOH}$  (lepidocrocite), while Jaffer and Hansson identified  $\gamma\text{-Fe}_2\text{O}_3$  (maghemite) (Jaffer and Hansson, 2009). The most expansive corrosion product detected to date in reinforced concrete is  $\beta\text{-FeOOH}$  (akaganeite), which is approximately 3.5 times the original volume of iron (Marcotte and Hansson, 1998, 2003). The reasons for such variance in observations remain unclear, however. The lack of information on the mechanism of depassivation of steel bars in the presence of chloride ions, and the interaction between passive and active regions (anode to cathode ratio) at the nano/micro scale, may be one reason. One difficulty in determining the type of corrosion products,

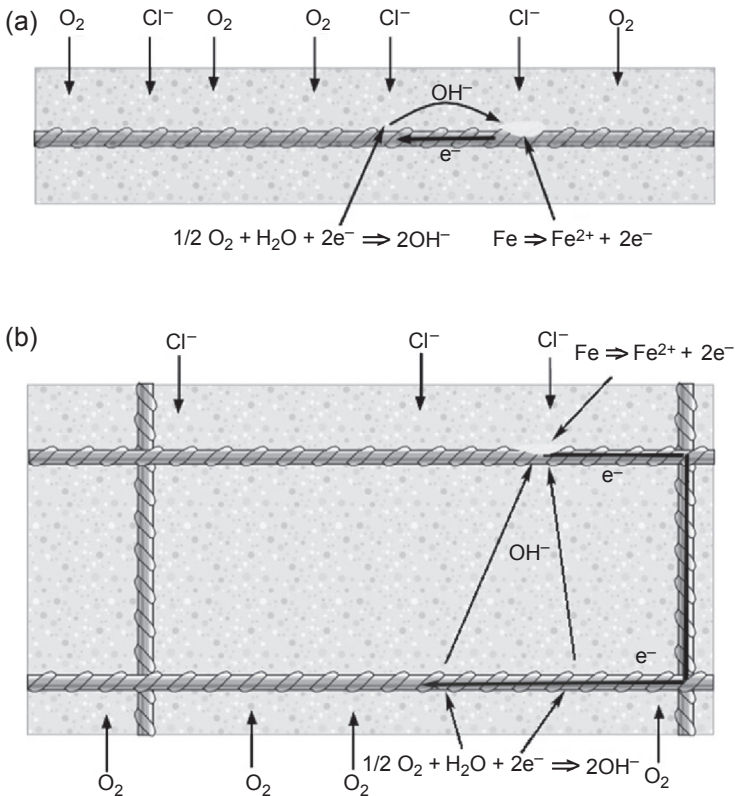


**Figure 2.3** Volume of corrosion products relative to iron.

and consequently the volume of products, is that the corrosion product from the steel is unstable in air and changes almost immediately upon exposure to the atmosphere for laboratory analysis. An in situ study of corrosion products (e.g., with Raman spectroscopy and scanning electrochemical microscopy) would be advantageous because it would provide more precise information on the volume and distribution of corrosion products.

## 2.8 Macrocell and microcell corrosion

Microcell corrosion is the term given to the situation where the active dissolution and corresponding cathodic half-cell reaction (the reduction of dissolved oxygen) take place at adjacent parts of the same bar, as illustrated in Figure 2.4(a). This process always occurs in practice, and in most cases is the dominant corrosion process. Macrocell corrosion can occur when the actively corroding bar is coupled to another bar that is passive because of either its different composition or its different environment. For



**Figure 2.4** Schematic illustration of (a) microcell corrosion and (b) macrocell corrosion.

example, the former situation might occur when black steel is in contact with stainless steel, and the latter when a top mat in chloride-contaminated concrete is coupled to a bottom mat in chloride-free concrete, as in [Figure 2.4\(b\)](#).

Macrocells can also form on a single bar exposed to different environments within the concrete or where part of the bar extends outside the concrete. The process is the same in all cases, and in all cases the corrosive action of the macrocell is added to those of the microcells. It should be emphasized that the simplified view of the “active steel becoming the anode and the passive steel becoming the cathode” is not actually correct. In each case, anodic and cathodic reactions occur on both metal surfaces; when the two metals are coupled, anodic corrosion of the active metal increases and anodic corrosion of the passive metal decreases. While macrocell corrosion can be measured directly, the same is not true of microcell corrosion, and most investigators choose to neglect the microcell component. This has led to the general assumption that macrocell corrosion is always the dominant component.

In the study by [Hansson et al. \(2006\)](#), it was concluded that for carbon steel in Ordinary Portland Cement (OPC) concrete with a relatively low electrical (ionic) resistance, the macrocell and microcell corrosion components were of the same order of magnitude and could be added together to provide the total corrosion rate on the actively corroding bar. In this case, the total corrosion rate was approximately three times that of the macrocell rate alone. In contrast, the macrocell corrosion of carbon steel in concrete with fly ash, silica fume, and slag was negligible, and corrosion was limited to the microcells on the top bar by the ionic resistance of the concrete. Therefore, care must be taken in using the results of macrocell measurements. The absence of macrocell corrosion cannot be taken as an indicator that microcell corrosion is not occurring.

## 2.9 Corrosion under load

Two electrically connected dissimilar metals in contact with an electrolyte can form a galvanic cell to produce a corrosive attack. Alternatively, either one metal or two similarly coupled metals immersed in two different environments can form a galvanic cell, as can applied stress ([Uhlig, 1985; Jones, 1995](#)).

In their use of steel bars in simulated concrete pore solutions to determine passive behavior under loads and repassivation after loads were removed, [Feng et al. \(2011\)](#) noted much more severe damage to passive layers under higher loads, which were hardly affected by the loading time change. In these applications of various loads, they also observed that steel under lower loads did indeed repassivate after the load was removed, but did not behave similarly under higher loads, which resulted in plastic deformation. They did not determine, however, how compressive stress loads and chloride ions affect depassivation, and their experimental procedure was questionable. Specifically, this investigation was flawed in that the samples were immersed in a concrete pore solution for 24 h to form the passive layer, which based upon the previous experience is insufficient time for forming a protective layer ([Poursaeed and Hansson, 2007](#)). Also, the cold-air drying of samples rendered them vulnerable to a pH of less

than 9, at which point the steel loses its passivity, meaning that the layer on the steel surface is a poor representation of the passive layer of steel within concrete. Finally, neither the presence of chloride ions nor their synergic effect on loading was considered when studying the depassivation of steel.

Zhang and Poursaei (2014, in press) also studied carbon steel passivation and depassivation from chloride attack in concrete simulated pore solution under different loading types. They determined that in a chloride-free pore solution, the corrosion rate in a passive state is less for specimens under tensile stresses than for specimens under compressive stresses. Specifically, we determined that the passivation of steel under tensile stress occurs more rapidly than it does under compressive stress, and that the electrode potential of the specimens under tensile stresses becomes more noble with increasing tensile stress. Conversely, an increase of the compressive stress caused a minor decrease in the nobility of the potential. In pore solutions contaminated with chloride ions, we observed that in spite of more rapid passivation and more protective passive layers formed during applications of tensile stress, specimens (previously passivated in chloride-free pore solution) under tensile stresses corroded faster than those under either compressive stresses or no stress. Zhang and Poursaei (2014) also noted that specimens exposed to chloride ions under compressive stresses exhibited superior performance compared with specimens under tensile load or no loading. Regardless of later placing protective passive layers under tensile stresses in the absence of chloride ions, this layer cannot protect the steel effectively when exposed to such chloride ions, thus showing that the degree of tensile stress has a greater impact on corrosion than does the passive layer's ability to protect steel against it.

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