APPENDIX A – BASICS OF CORROSION OF METALS

Metals are commonly created by refining naturally occurring stable ores and minerals by using large amounts of heat energy (e.g. blast furnace). The reconfigured ores and minerals in the form of metals are in an unstable state compared to their naturally occurring stable states. Corrosion is nature's way of returning metals to their unrefined naturally occurring forms as ores and minerals. The product of the corrosion process in iron-based metals is rust (ferric oxide) and hence corrosion is also known as rusting. The corrosion process releases the energy the metal gained during its refining in the form of electrical energy (FHWA, 1990).

For corrosion to occur, the following three conditions must be satisfied:

1. Presence of an electrolyte, such as water, which can conduct electrical current. Sometimes gases can also serve as electrolytes.

2. Presence of dissolved substances in electrolyte. Examples of dissolved substances include gases such as oxygen and chlorine and/or dissolved hydrogen ions.

3. The development of a "corrosion cell" wherein two portions of like or unlike metal surfaces become electrically connected via an electrolyte

The corrosion process is a natural electrochemical process where electron flow occurs in the steel and at the same time hydroxide ions are conducted through an electrolyte. This completes an electric circuit. The completed circuit is known as a corrosion cell. A schematic of a typical corrosion cell is shown in Figure 4. A corrosion cell is an electrochemical cell that acts very much like a battery. As shown in Figure 4, the corrosion reaction consists of simultaneous cathodic and anodic reactions. The steel acts as an electrode that couples the two reactions as discussed below (Hamilton, et al., 1995; Key to Metals.Steel, 2009):

Anodic reaction: $Fe \rightarrow Fe^{2+} + 2e^{-}$

Cathodic reaction: $2H_2O + O_2 + 4e^{-} \rightarrow 4(OH^{-})$

Hamilton, et al. (1995) note that in sound, uncracked and uncontaminated grout these reaction rates are depressed to a sufficiently low level because of the protective oxide layer that forms over the surface. The amount of iron lost to corrosion is insignificant over the life of a typical structure. An environment with an elevated pH (>13) and oxygen is required for this protective or passive layer to form. The presence of sodium, potassium, and calcium hydroxides derived from the reactions between the mix water and Portland cement provides an environment suitable for the passivation of the steel. Consequently, grout can provide excellent corrosion protection in two ways, (1) by maintaining the alkaline environment surrounding the surface of the grout necessary to passivate the steel, and (2) by providing a tough barrier to the external elements. However, the problems begin when the grout is no longer sound and/or contaminated.

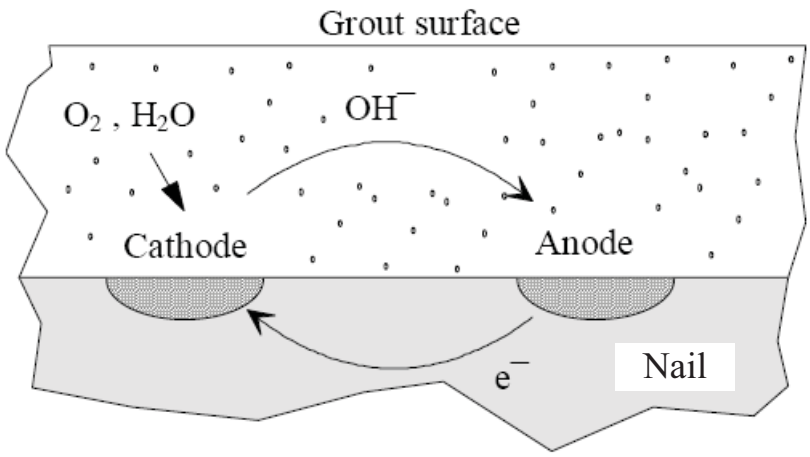

Figure 4: Schematic, Representation of corrosion of steel in uncracked grout (after Hamilton, et al. 1995).

The structural durability of this mechanism is a function of the grout quality and the depth of cover. It is important that the pH not be reduced because corrosion accelerates when the pH approaches a value of 7.0 (Houston, et al., 1972). The pH can reduce (a) by carbonation wherein the cementitious grout reacts with various corrosive elements or (b) by direct access of corrosive elements to steel via cracks in the grout body. Carbonation occurs when carbon dioxide combines with moisture in the pore structure of the grout to form carbonic acid which neutralizes the alkalinity of the grout by reducing the pH to less than 9. The following simplified equation describes the process:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$

in the presence of H_2O and NaOH

When the pH is reduced, the passive film is destroyed, which leads to steel corrosion and the formation of rust. Rust occupies a volume approximately 10% greater than the steel from which it formed. Therefore, rust exerts expansive stresses on the surrounding grout. Because the grout has low tensile strength, these expansive stresses can cause cracking and spalling, which, in turn, permit faster ingress of water, oxygen, and chlorides, into the grout thereby accelerating corrosion further.

In a corrosion cell, these reactions can continue in a cycle. The total reaction will normally be under cathodic control. Figure 5 illustrates the corrosion cell in the event of the grout cover being carbonated by corrosive agents. If the grout cover is cracked and the cracks extend to the steel bar, then the steel exposed in the bottom of a crack becomes the anode in a galvanic cell. In this case the reinforcement in the uncracked grout becomes a cathodic area and this is very large compared to the area of steel in the crack. Thus, the cathodic capacity would be large, giving a very high current density on the anode; i.e., extremely rapid corrosion occurs (Fidjestol

and Nilsen, 1980). This is the reason why cracked grout is a major concern in tensioned elements such as soil nails.

The corrosion can be uniform or localized. Uniform corrosion causes a uniform loss of metal across the entire surface of the element, while localized corrosion causes pitting at a specific point on the element.. In either case, the rate at which the electrons move out of the metal is the principal factor controlling the corrosion rate and is of primary interest in the corrosion process.

Many factors affect the development and rate of corrosion. These include soil resistivity, moisture content, soluble salts, chlorides, sulfates, sulphides, pH, redox potential, soil texture and density, oxygen transfer, organic material and soluble iron content.

For a more detailed discussion on corrosion of soil reinforced structures, the reader is referred to FHWA (1990).