CORROSION OF STEEL REINFORCEMENT IN REINFORCED CONCRETE STRUCTURES – EFFECT AND METHODS OF REPAIR

By

Soliyana Ejigu

A Thesis Submitted to

The School of Civil and Environmental Engineering

Presented in Partial Fulfillment of the Requirements for the Degree of Master of Science in Civil Engineering (Structural Engineering)

Addis Ababa University

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ABSTRACT

Corrosion of Steel Reinforcement in Reinforced Concrete Structures – Effect and Methods of Repair

Soliyana Ejigu

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Reinforced concrete structures have the potential to be very durable and capable of withstanding a diversity of adverse environmental conditions. However, failures in structures still occur as a result of variety of defects among which premature reinforcement corrosion is one.

In the case of concrete structures, the main effect of the reinforcement corrosion is its section decreases due to the corroding process. Reduction of reinforcement thickness then leads to loss of mechanical strength and structural failure or breakdown.

In this thesis, the chemistry of corrosion in concrete is briefed. The damages caused by corrosion of steel in concrete, corrosion detection measurement in built structures and corrosion consideration in developed countries are also discussed.

Since much attention is not being given to corrosion effect in Ethiopia construction industry, some sample pictures are collected from construction sites and is attempted to show the corrosion consideration in our country.

Poor construction methods and workmanship could attribute to the failure of structures. The poor construction methods and workmanship is caused due to negligence and inadequate quality control at construction sites. The study discloses that labor and money could be saved by means of repair and rehabilitation; and serious accidents could be avoided if the corrosion of reinforcements is well understood, detected and monitored at early stage.

Key words: Corrosion, Reinforcing steel, Repair, Rehabilitation and failure

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List of Symbols

Fe	Iron
e-	Electron
O2	Oxygen
OH-	Hydroxide ion
H+	hydrogen ion
Cl-	chloride ion
Kg	Kilogram
mm	millimeters
UK	United Kingdom
USA	United States of America
£	Pound sign
$	dollar sign
Cm	Centimeter
V	Volt

1. INTRODUCTION

1.1. BACKGROUND

For thousands of years, humans have taken advantage of ductile materials with high tensile strength in the reinforcement of brittle materials having high compressive strength. The ductile reinforcement transfers tensile loads in the structure, allowing the brittle material to crack without causing failure of the structure. During the last two centuries, concrete has been developed into a construction material with ever increasing potential to support compressive forces. As the compressive capacity of concrete increased, the demand to support larger and taller structures becomes eminent and hence, stronger, more ductile and more tensile reinforcement has been required[1].

Reinforced concrete structures have the potential to be very durable and capable of withstanding a variety of adverse environmental conditions. However, failures in the structures do still occur as a result of variety of defects among which premature reinforcement corrosion is one.

As a modern construction material, steel has been used to reinforce concrete since it provides tensile strength, ductility and chemical bond for the structure. It comes in round and plain forms. Unfortunately, steel is subject to corrosion in wet and salty environments. Due to this, the steel become weak and lose some of its important properties. Many issues pertaining to the corrosion of steel in such a medium are unsolved and most scientists and engineers are still unfamiliar to corrosion, and hence need a thorough investigation. In addition, concrete is quite different from the traditional aqueous corrosion media, some theories and techniques used in the traditional corrosion field may not be directly applicable to the study of corrosion of reinforced concrete.

Steel has the ability to bond with the surrounding concrete. This formation of bond is a significant property of reinforcing steel allowing forces to be transferred and distributed evenly to the surrounding concrete material. The physical interlocking of the concrete aggregate, the quality and strength of concrete in tension and compression, bar deformations, the anchorages within the concrete at the reinforcement ends are the products of bond strength between steel and concrete. Much of the research and development on rebar throughout its history attempted to determine and increase the bond strength of reinforcing elements in concrete.

Reinforced concrete structures were considered to be highly resistant to corrosion due to the presence of concrete cover. However, practically, reinforced concrete structures usually do not perform so well, and their service lives are sometimes much shorter than what they were designed for. The steel in concrete is always attacked by corrosion. This leads to become at a reasonable explanation that the cover concrete is not free of defects.

Corrosion of reinforcement has been established as the predominant factor causing widespread premature deterioration of concrete construction worldwide, especially of the structures located in the coastal marine environment and in areas of subsoil possessing salinity. After the ingression of chloride ions and carbon dioxide to the steel surface, the corrosion process continues and the corrosion products (iron oxides and hydroxides) deposit around the steel and develop expansive stresses and cause the concrete cover to crack and spall. This results in progressive deterioration of the concrete.

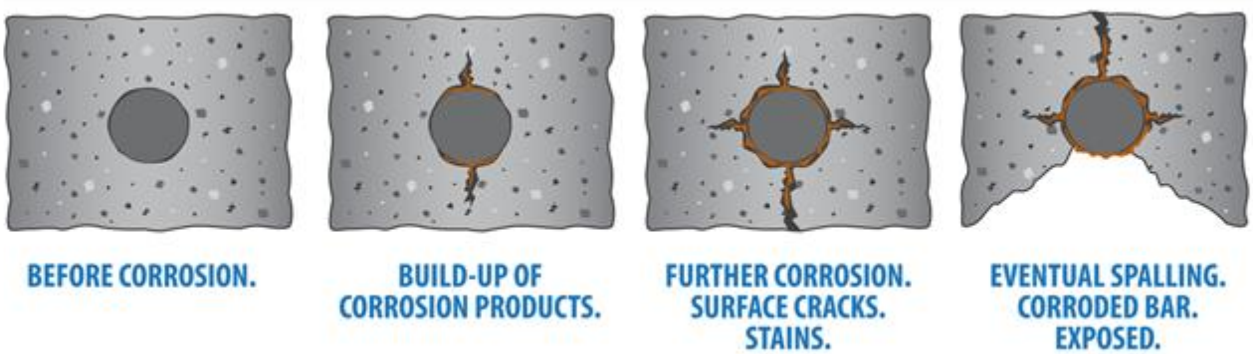

Figure 1.1 Buildup of corrosion products, spalling of concrete cover and exposure of reinforcements

Consequently, the repair costs nowadays constitute a major part of the current spending on infrastructure. It is desirable to monitor the condition of such strategic structures right from the construction stage by carrying out periodic corrosion surveys and maintaining a record of data. Quality control, maintenance and planning for the restoration of these structures need non-destructive inspections and monitoring techniques that detect the corrosion at an early stage.

Corrosion loss consumes considerable portion of the budget of the country by way of either restoration measures or reconstruction. There have been a large number of investigations on the problems of deterioration of concrete and the consequent corrosion of steel in concrete. Properly monitoring the structures for corrosion performance and taking suitable measures at the appropriate time could affect enormous saving. Moreover, the repair operation themselves are quite complex and require special treatments of the cracked zone, and in most instances the life expectancy of the repair is limited. Accordingly, corrosion monitoring can give more complete information of changing condition of a structure in time,[5].

If the corrosion of reinforcement could be understood, detected and monitored and suitable measures could be taken to prevent, or even only to delay the corrosion damage, then greater amounts of labor and money could be saved in repair and rehabilitation, and potentially serious accidents could be avoided. This is of great significance for authorities or organizations that are responsible for managing reinforced concrete structures,[6].

In our country, no specific defect due to corrosion is separately recorded as the method of identification is only physical. As the problem of corrosion essentially produces damage with respect to durability, less importance is given. Thus, this study shall focus in corrosion damages caused defectsand rectification of reinforced concrete structures.

1.2. OBJECTIVES OF THE THESIS

The general objective of this thesis is to study effect of corrosion of steel reinforcement in reinforced concrete structures such as buildings and bridges susceptible to such damages.

The specific objective is to show that corrosion of steel is a major concern.Thus, the study shall address method of identifying the problems that cause corrosion, effects of corrosion on structures, corrosion consideration in the Ethiopian practice and suggesting corrosion prevention methods.

1.3. OUTLINE OF THE THESIS

This thesis is devoted to the study of corrosion of steel in reinforced concrete structures where the chemistry of corrosion, consequences of corrosion and factors that affect corrosion of reinforcing steel in reinforced concrete structures is considered.

In addition, the corrosion consideration in the Ethiopian practice considering corrosion treatment in built structures and corrosion of reinforcements in construction sites are addressed.

In the light of these, the thesis is organized as follows:

Chapter 1: addresses the background of the corrosion problems in view of explaining the objectives of the study. Moreover, the content of the study is also disclosed.

Chapter 2: deals with literature review where corrosion process including chemistry of corrosion, factors affecting corrosion of reinforcing steel in concrete structures, consequences of corrosion, its detection and measurement and its consideration in developed countries are dealt.

Chapter 3: presents corrosion consideration in Ethiopian practice focusing on reinforcement corrosion consideration in construction sites and corrosion in already built structures.

Chapter 4: describes reinforcement corrosion protection methods such as general design and construction provisions. Furthermore, the chapter focuses on how to select protection systems and how to develop awareness on the problem.

Chapter 5: focuses on corrosion control measure such as corrosion inhibitors, field performance of epoxy-coated reinforcing steel and corrosion resistant reinforcing bars as well.

Chapter 6: is devoted to repair of corrosion affected reinforced concrete structures. Materials for repair, structural repair based on extent of damage and also repair of severely corrosion damaged member are also discussed.

The last chapter of this thesis is made to address the conclusion and recommendations for future work.

2. LITERATURE REVIEW

2.1. GENERAL

Steel, like most metals except gold and platinum, is thermodynamically unstable under normal atmospheric conditions and will release energy and revert back to its natural state—iron oxide, or rust. This process is called corrosion.

Corrosion is the deterioration of metallicmaterials by chemical interaction with their environment. The term corrosion is sometimes also applied to the degradation of plastics, concrete and wood, but generally refers to metals. The most widely used metal is iron (usually as steel) and the following discussion is mainly related to its corrosion, [6].

2.2. CORROSION PROCESS – CHEMISTRY OF CORROSION

Corrosion is an electrochemical process involving the flow of charges(electrons and ions). At active sites on the bar, called anodes, iron atoms lose electrons and move into the surrounding concrete as ferrous ions. This process is called a half-cell oxidation reaction, or the anodic reaction, and is represented as:

$$2Fe \rightarrow 2Fe^{2+} + 4e^{-} \quad (2.1)$$

The electrons remain in the bar and flow to sites called cathodes, where they combine with water and oxygen in the concrete. The reaction at the cathode is called a reduction reaction. A common reduction reaction is:

$$2H_2O + O_2 + 4e- \rightarrow 4OH^{-} \quad (2.2)$$

To maintain electrical neutrality, the ferrous ions migrate through the concrete pore water to these cathodic sites where they combine to form iron hydroxides, or rust:

$$2Fe^{2+} + 4OH^{-} \rightarrow 2Fe(OH)_2 \quad (2.3)$$

This initial precipitated hydroxide tends to react further with oxygen to form higher oxides. The increases in volume as the reaction products react further with dissolved oxygen leads to internal stress within the concrete that may be sufficient to cause cracking and spalling of the concrete cover.

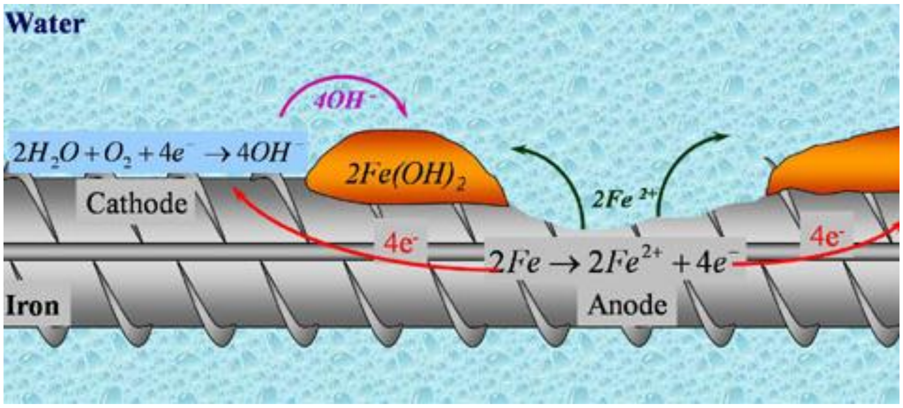

Figure 2.1 Oxidation process of reinforcing steel

2.3. CORROSION PROCESS OF REINFORCING STEEL IN CONCRETE

Generally, corrosion of metal in any environment consists of the following basic processes:[6]

- Depolarization reagent arrives at the surface of metal through the medium surrounding it. Commonly the depolarization reagent is oxygen dissolved in the medium or proton (H+) naturally existing in the aqueous medium.
- Electrochemical (anodic and cathodic) reactions occur at the interface between the metal and the surrounding medium, i.e. most probably, the oxidization of metal and the reduction of O_2 or H^+.
- Reaction products (corrosion products) are accumulated at the surface of metal or removed away from the surface into the medium. For example, passive film or iron rust is formed at the surface of metal; or generated hydrogen gas, OH- and Fe^{2+} during the corrosion process move away from the surface of metal into solution.

It should be borne in mind that these three basic processes are essential for any corrosion of metal. The absence or stopping of any one of the processes will end the progress of corrosion.

Due to the porosity of concrete, O_2 can easily diffuse into concrete, becoming dissolved in the pore solution and finally reaching the surface of steel. At the surface (cathodic area), oxygen is reduced into hydroxide ion via an electrochemical cathodic reaction.

$$O_2 + 2H_2O + 4e \rightarrow 4OH^- \qquad (2.4)$$

This is a very common cathodic reaction associated with most corrosion of steel in concrete. However, in some special cases, the cathodic reaction may be in the form of hydrogen evolution:

$$2H_2O + 2e \rightarrow H_2 + 2OH \qquad (2.5)$$

Equation (2.5) might occur in two cases:

1) At a very negative potential or a very high cathodic current density;
2) In a carbonated concrete in which the pH value of the pore solution has become very low.

Even in these two cases, reaction by equation (2.4) still has some contribution to the corrosion of steel, but the effect of reaction (2.5) prevails over reaction (2.4). No matter which process is taking place, the cathodic reactions always produce hydroxide ion and increase the pH value of pore solution in the vicinity of cathode.

The anodic reaction occurring at the anodic area on the steel surface can be basically described as a reaction:

$$Fe \rightarrow Fe^{2+} + 2e \qquad (2.6)$$

With this anodic reaction proceeding, the cross section of steel bar is reduced and finally the rebar could break down. So reaction (2.6) is a very important process responsible for the corrosion damage of reinforcement.

The intermediate corrosion product, $Fe^{2+,}$ could be further transformed into Fe^{3+} under oxidizing conditions, and be accumulated at the surface of steel rebar; or be dissolved into the pore solution and move away from the steel reinforcement, under reducing conditions.

Normally, the pore solution is rich in oxygen with a high pH value. So Fe^{2+} can stay in the form of $Fe(OH)_2$ or $Fe(OH)_3$ due to hydrolysis or oxidation of Fe^{2+}, forming a thin passive film on the steel surface, which consequently retards reaction (2.6). In this case, the steel can be well protected in concrete, and there will be no detectable corrosion damage.

However, at the initial stage after concrete is casted and subjected to moist-curing, the passive film cannot be formed so quickly if the concrete is completely immersed in water. It was suggested that the formation of passive film on reinforcement might take a significantly long time even when the concrete is not completely immersed in water after casting. This is understandable, because in a very basic solution, steel cannot be passivated as easily as stainless steel; also the supply of oxygen which is necessary for the passivation of steel in concrete is usually a few orders of magnitude lower than that in a normal aqueous solution.

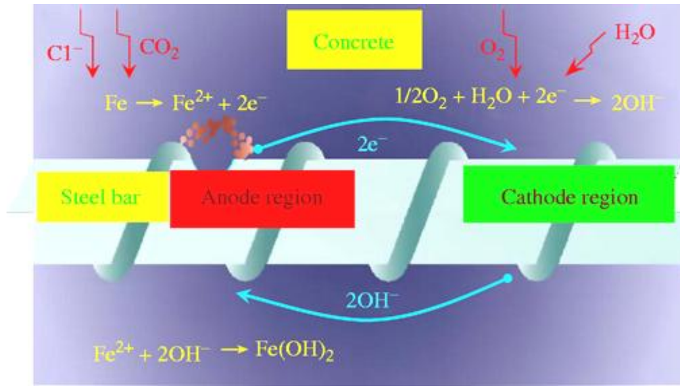

Figure 2.2 Corrosion process of reinforcing steel in concrete

2.4. TYPES OF CORROSION OF REINFORCING STEEL IN CONCRETE STRUCTURES

Corrosion in steel reinforcement may take the following forms:[4]

2.4.1.CREVICE CORROSION

Crevice corrosion is a localized form of corrosion usually associated with a stagnant solution on the micro-environmental level. Such stagnant micro environments tend to occur in crevices (shielded areas). Oxygen in the liquid which is deep in the crevice is consumed by reaction with the metal. Oxygen content of liquid at the mouth of the crevice which is exposed to the air is greater, so a local cell develops in which the anode, or area being attacked, is the surface in contact with the oxygen-depleted liquid.

2.4.2.PITTING

Theories of passivity fall into two general categories, one based on adsorption and the other on presence of a thin oxide film. Pitting in the former case arises as detrimental or activator species, such as Cl^-, compete with O_2 or OH- at specific surface sites. By the oxide film theory, detrimental species become incorporated into the passive film, leading to its local dissolution or to development of conductive paths. Once initiated, pits propagate auto-catalytically according to the generalized reaction,

$$M+3 + nH2O + nCL- \rightarrow M(OH)n + nHCL, \quad (2.7)$$

resulting in acidification of the active region and corrosion at an accelerated rate (M+n and M are the ionic and metallic forms of the corroding metal).

2.5. FACTORS AFFECTING CORROSION OF REINFORCING STEEL IN CONCRETE STRUCTURES

The corrosion behavior of reinforcement steel in concrete is a function of parameters of steel and concrete as well as the properties of their interfacial zone. That is, it is determined by the composition of the pores solution of the concrete and chemical properties of the steel. The other parameters of concrete would affect corrosion of steel through their influences on the pore solution.

Environmental factors can not affect the corrosion processes directly, but they cause the deterioration of the cover concrete and accelerate the ingress of aggressive species, making the pore solution in contact with the steel more corrosive. Among all the environmental factors, chloride ions and carbon dioxide have been responsible for most corrosion of steel in concrete structures. In Addition to these two factors, temperature and moisture, as well as some other factors that cause deterioration in concrete, also play important roles in corrosion of steel in concrete. What makes the influence of those factors so complicated is that the corrosion of steel in concrete is not determined by a single factor. The interaction among these factors plays an important role in the corrosion process of the steel reinforcement, [6].

2.5.1. REINFORCING STEEL

Different types of steels have different microstructures and compositions so different types of steel usually have different corrosion behaviors in concrete.

The steel surface can directly affect the bond between the reinforcement and the concrete, and further influence the failure of structures. It was found that the rust which was well adhered to the underlying steel helped the bond between steel and concrete. The surface of steel treaded with water to form a coating before incorporation of the steel in concrete could increase the bond strength. Slight corrosion could increase the bond strength, whereas severe corrosion decreased it.

2.5.2. PORE SOLUTION OF CONCRETE

The pore solution in concrete is an electrolyte which is physically absorbed in the pores of the concrete due to the capillary force produced by absorption resulting from molecular force. It reacts with the steel reinforcement and under certain conditions can lead to the corrosion damage at the steel surface.

2.5.3. PERMEABILITY OF CONCRETE

Higher porosity and larger pre sizes lead to more severe corrosion damage in the steel. The pores can facilitate the ingress of Cl^-, CO_2, O_2, H_2O and some other detrimental species from the environment. They also greatly affect the removal of corrosion products from the steel surface. Therefore, the permeability directly affects two of the basic corrosion processes, the supply of depolarization reagents and the removal or accumulation of corrosion products and has significant influence on the corrosion of reinforcement.

For a normal concrete structure, it is believed that oxygen is very easily able to access the reinforcement but it is quite difficult for corrosion products to move from the reinforcement surface. In effect, resistivity of concrete can be partially ascribed to the permeability as well, so the permeability of concrete also exerts an influence on the galvanic corrosion rate through its influence on the ion flowing process in the cover concrete.

If the concrete has low permeability, then the aggressive species would be difficult to access the reinforcement, and the possibility of corrosion of the reinforcement would be low.

The permeability of concrete is mainly determined by the porosity of concrete and its pore size distribution, which are dependent on the ratio of water/cement (w/c) in the concrete. Therefore, the permeability of concrete increases with an increase in w/c ration, especially when w/c >0.55 . Sometimes, the permeability of concrete could vary by as much as two orders of magnitude as w/c increases from 0.4 to more than 0.7.

Other factors can also significantly affect the permeability of concrete. For example, hydration process of cement also influences porosity and permeability. It was found that the porosity for hardened cement paste changed from 29% at age 40 days to 25.8% at age 296 days. The use of mineral admixture (fly ash) also had significant effect on the chloride diffusion than on the oxygen diffusion in concrete.

Low w/c, better compaction and use of mineral admixtures etc, could lower the permeability of the cover concrete, therefore they are the options to improve the corrosion resistance of reinforced concrete.

2.5.4. MOISTURE

The influence of concrete moisture content on the rate of corrosion of steel in concrete is well known. If there is no water in concrete, there should be no corrosion problem with the reinforcement. Since electro chemical reactions are mainly responsible for the reinforcement corrosion, moisture should be an essential substance in the corrosion of steel in concrete, [6].

The moisture of concrete has a complicated influence on the corrosion of steel in the concrete. The resistivity of concrete is first affected by the moisture, which can influence the galvanic corrosion rate. However, increasing moisture has contrary effects on anodic and cathodic reactions. The anodic reaction rate increases and the cathodic reaction rate decreases with the increasing humidity. This is due to the fact that the increase in moisture makes the departure of rust or corrosion products easier, but it decreases the diffusion coefficient of oxygen and makes the supply of oxygen more difficult.

In recent years, research interest has been increasing in the rate of water absorption into cover concrete. The water absorption into concrete from outside environment can rapidly increase the rate of corrosion of depassivated reinforcing steel to the levels that will cause cracking and spalling. The absorption is also an important transport mechanism for the ingress of chlorides into concrete. It was found that the internal relative humidity (RH) of concrete behaved differently to the external RH; but no direct relationship was found between corrosion rate and internal RH or temperature.

2.5.5. CHLORIDE

Chloride in concrete is a main cause of corrosion of reinforcement. Most of the damages in concrete structures are caused by chloride – induced corrosion.

The main characteristics of chloride-induced corrosion are as follows:

- Anodes and cathodes are separated, and corrosion rate is very high and localized.
- Once the corrosion is initiated, it is far more difficult to remedy that carbonation.

Chloride comes from different sources. It can be cast into concrete in the following ways:

- Deliberate addition of chloride as accelerators;
- Use of water containing Cl^-;
- Contaminated aggregates.

Chloride can also diffuse into concrete as a result of:

- Sea salt spray and direct sea water wetting;
- Deicing salts;
- Use of chemicals.

Normally, the chloride exists in concrete in two forms:

- Dissolved in pore solution as free chloride;
- Absorbed on cement gel or combined with hydrated cement and aggregates as bound chloride.

Only the free chloride can accelerate corrosion of steel in concrete. The bound chloride is inert to steel before it is dissolved into solution and becomes free chloride.

The relationship between free chloride and bound chloride is affected by binder type, degree of hydration, amount of pore solution and other ions in the pore solution.

Some other factors such as curing temperature, curing age, original alkalinity also affect the chloride binding capacity of concrete. It has been suggested that the presence of super-plasticizer in concrete could lower the chloride binding capacity. The chloride uptake and the pore solution composition in concrete were affected by drying/wetting and temperature, but the effects were influenced by chloride concentration; carbonation strongly decreased the chloride uptake and reduced the chloride concentration of concrete.

2.5.6. CARBON DIOXIDE

Carbonation of concrete is another main cause of corrosion of steel reinforcement. Carbonation is a result of the reaction of carbon dioxide in the atmosphere with the hydroxides in the concrete. This lowers the PH value of the pore solution. The corrosion reaction of steel in concrete is dramatically enhanced when the PH of the solution falls below 9.

Carbonation can affect the diffusion of chloride in concrete through changing the pore structure of concrete. A reduction of total porosity and a redistribution of pore sizes as a result of carbonation; the proportion of large pores increased. In addition, the chloride binding capacity is decreased with carbonation due to the change of the cement gel into relatively coarse crystalline products and the decrease in the PH of pore solution.

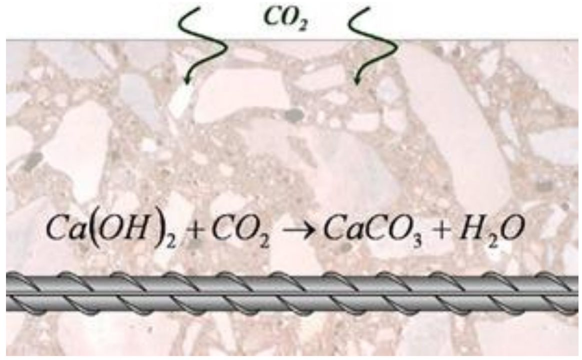

Figure 2.3 Carbonation process

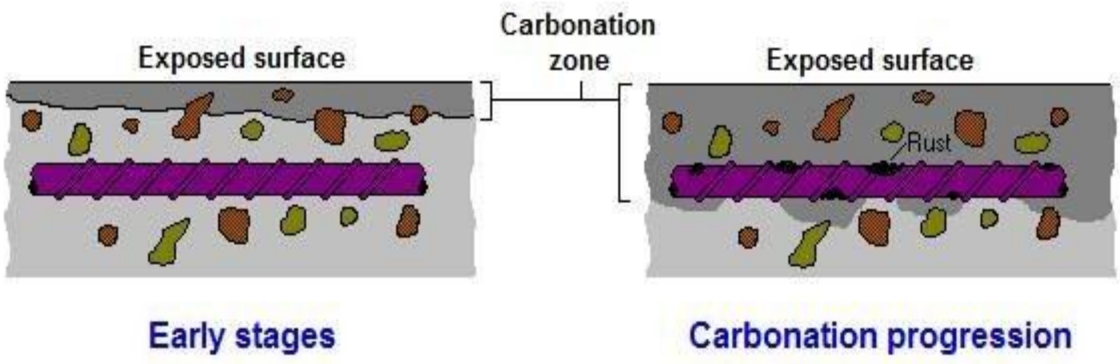

Figure 2.4 Carbonation leads to the general corrosion along the full length of the bar.

2.5.7. COMPONENTS OF CONCRETE

Any factor that affects the pore solution and the porosity of concrete would affect the corrosion of steel in concrete. The types and quantities of binder, aggregate and w/c ratio can determine the performance of concrete to some extent. Workmanship and curing are other important factors that influence the corrosion process of steel in concrete. If these factors could be well controlled, the corrosion performance of reinforced structures would be much improved. Concrete formulation of the main components of concrete can be one of the effective approaches to enhance corrosion resistance of reinforced concrete.

2.5.8. CONCRETE RESISTIVITY

The electrical resistivity of hardened cement paste, mortar and concrete has been widely reported as significantly affecting the corrosion of reinforcement in concrete, [6].

The resistivity of concrete is determined by the pore solution concentration, the microstructure of the concrete (pore size and its distribution), the moisture and salt content as well as the temperature.

Resistivity decreases as temperature increases; and the effect of temperature is approximately a 3% change in resistivity per 1^0C.

Resistivity of concrete directly affects the ionic current flow, and consequently influences the galvanic corrosion activity. A concrete, which contains a high concentration of chloride and a relatively high level of moisture, usually corresponds to a low resistivity. Therefore, there is a relationship between the corrosivity and resistivity of concrete.

2.5.9. THICKNESS AND DEFECTS OF COVER CONCRETE

The thickness of cover concrete determines the time for aggressive species to reach the steel rebar in concrete. Sometimes the service life of reinforced concrete structures can be extended greatly simply by increasing the thickness of the cover concrete. The normal thickness for most structures is around 50mm. However, not all parts of structures can strictly follow the designed cover thickness. Field studies showed that encroachments on specified cover did occur and were widespread; 62% of the buildings surveyed had over thickness less than specified, [6].

Compact and defect-free concrete tends to be resistant against corrosion of steel reinforcement. Unfortunately, there are no defect-free materials, and almost all the international codes of reinforced concrete designs are related with permissible crack widths. The detrimental effect of cracks in concrete on corrosion of the embedded reinforcement is obvious. Numerous studies were carried out to describe the reinforcement corrosion in the cracked zones. Some of them dealt with the chloride-induced corrosion of steel in the crack zone. Cracks in concrete make the corrosion of reinforcement occur more readily than in un-cracked concrete; anodic dissolution of steel can be facilitated in cracked concrete.

2.5.10. TEMPERATURE

Temperature can influence corrosion rate of reinforcement in concrete. All the processes involved in corrosion (i.e. anodic and cathodic electrochemical reactions, transport of aggressive species to steel surface, accumulation of corrosion products on the steel surface or departure from the interface of steel/concrete, and ionic flow through concrete) can be influenced by temperature. Increases in temperature will lead to increasing rates of all these processes, consequently an increase in corrosion rate. It was reported that two folds higher corrosion rate could be reached by only 10^0C increase in temperature, [6].

The accelerating effect of temperature on chemical reactions is well known, but its effect on concrete chemistry, which can affect corrosion of reinforcement corrosion, is not widely reported.

In field structures, the temperatures are not the same at difference depths of cover concrete. The inner concrete or the reinforcement has a delayed response to the variation of environmental temperature.

2.5.11. CRACKS DUE TO MECHANICAL LOADING

Cracks in concrete formed as a result of tensile loading, shrinkage or other factors can also allow the ingress of the atmosphere and provide a zone from which the carbonation front can develop. If the crack penetrates to the steel, protection can be lost. This is especially so under tensile loading, for de-bonding of steel and concrete occurs to some extent on each side of the crack, thus removing the alkaline environment and so destroying the protection in the vicinity of the de-bonding, [4].

2.5.12. WATER – CEMENT RATIO

The ratio of water to cement has a very significant influence on the porosity of concrete. A higher water to cement ratio can produce a higher porosity concrete which is easily penetrated by aggressive species. Steel in such a concrete is more easily corroded. The water cement ratio in concrete has been founded to significantly influence the corrosion rate of steel in concrete; this influence was even more significant than the binder type, [6].

Concrete placed with a high water-cement ratio, is more porous due to the presence of excess water in the plastic concrete. The porosity increases the rate of diffusion of water and electrolytes through the concrete and makes the concrete more susceptible to cracking, [4].

2.5.13. LOW CONCRETE TENSILE STRENGTH

Concrete with low tensile strength facilitates corrosion damage in two ways. First, the concrete develops tension or shrinkage cracks more easily, admitting moisture and oxygen and in some cases chlorides, to the level of the reinforcement. Second, the concrete is more susceptible to developing cracks at the point that the reinforcement begins to corrode, [6].

2.5.14. ENVIRONMENT

The local environment of a structure substantially influences the rate of corrosion of exposed steel and the deterioration of the protective coating. Traditionally, corrosion engineers have classified the general (macro) environment surrounding a structure as mild (rural), industrial, moderate, or severe (marine). These general classifications are of some limited use to the bridge designer as a starting point for determining the appropriate level of corrosion protection required for the structure. The designer should begin by assessing the surrounding environment for the subject bridge with specific focus on the potential for salts or deleterious chemicals to contact and remain on the steel surfaces and for excessive amounts of moisture to remain on steel surfaces. For highway bridges the following types of environments are distinguished, [10]:

- Mild (Rural): Little to no exposure to natural airborne and applied deicing salts. Low pollution in the form of sulfur dioxide, low relative humidity, absence of chemical fumes, usually an interior (inland) location.
- Industrial: High sulfur dioxide or other potentially corrosive airborne pollutants, moderate or high humidity. This classification has become less important in recent years as long-term corrosion data shows the corrosive effects of airborne pollutants has diminished with the implementation of clean stack gas regulations. This atmospheric classification is still a consideration directly downwind of known corrosive process stream contaminants.
- Moderate: Some (occasional) exposure to airborne salts or deicing salt runoff.
- Severe (Marine): High salt content from proximity to seacoast or from deicing salt, high humidity and moisture.

2.6. DAMAGESCAUSED BY CORROSION OF STEEL IN CONCRETESTRUCTURES

The expansion associated [9]with rust is mostly due to hydrated oxides that may swell up to ten times the original volume of the steel. The type of corrosion product formed at the steel depends on environmental conditions:

- Red or brown rust forms under high oxygen concentrations, forming flakey rust which is relatively soft and easy to dislodge from the rebar.
- Black rust forms under low oxygen concentrations, forming a relatively dense and hard layer that may be difficult to remove from the parent steel.

Two major consequences of reinforcement corrosion are commonly observed, cracking and spalling of the cover concrete as a result of expansion of the corrosion product, and a reduction of cross-sectional area of the rebar by pitting.
Manifestations of corrosion depend on a number ofinfluences that include:

- Geometry of the element (large diameter bars at low covers allow easy spalling)
- Cover depths (deep cover may prevent full oxidation of corrosion product)
- Moisture condition (conductive electrolytes encourage well-defined macro-cells)

- Age of structure (rust stains progress to cracking and spalling)
- Rebar spacing (closely spaced bars in walls and slabs encourage delamination)
- Crack distribution (cracks may provide low resistance paths to the reinforcement)
- Service stresses (corrosion may be accelerated in highly stressed zones)

The loss of serviceability of corroded reinforced concrete structuresmay be described by a three phase damage model shown in Figure 2.3.

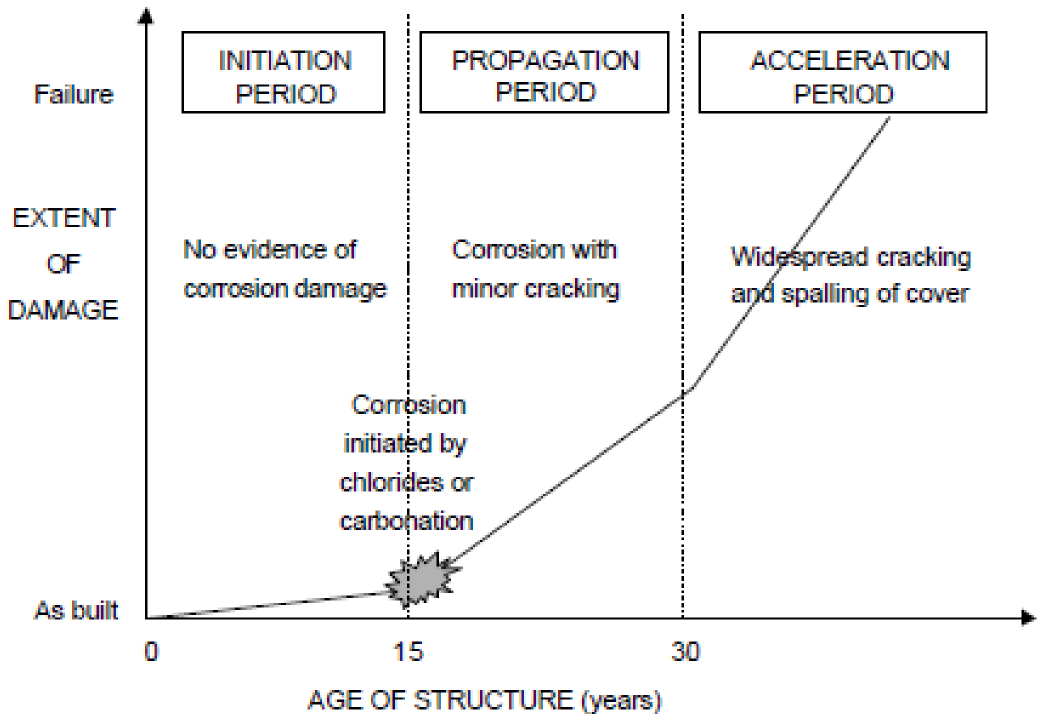

Figure 2.5 Three phase corrosion damage model

The different phases are defined as follows:

- **An initiation period** before corrosion is activated by either carbonation or chloride attack, during which negligible concrete deterioration occurs.
    - Estimating the initiation period - The assumption is made that corrosion initiates when the chloride content in the concrete reaches the critical level at the reinforcement. The time to initiation is calculated for each reinforcement bar, or group of bars, using Fick's 2nd law rearranged to make time the subject of the calculation:

$$T_{init} = \left[\frac{x}{2erfc^{-1}\left[\frac{C_{Crit} - C_i}{C_s - C_i}\right]} \right]^2 \quad D_{ce} \tag{2.8}$$

Where: C_{crit} = critical total chloride threshold level (% by mass of concrete)

Ci = initial total chloride content in the concrete i.e. from sea dredged aggregate or calcium chloride accelerator (%by mass of concrete)

C_s= total chloride content at the surface (% by mass of concrete)

D_{ce} = effective chloride diffusion co-efficient (m2/s)

T_{init} =initiation period (years)

$erfc^{-1}$ = inverse error function complement $(1 – erf)^{-1}$

x = depth below the exposed surface to the point being considered (m)

- **A propagation period** in which active corrosion commences and cracking of the cover concrete occurs due to the formation of expansive corrosion products at the steel surface.
  - Estimated time to cracking

    The percentage corrosion to cause cracking can be estimated from the following equation:

$$\Delta_{cr} = \frac{c}{2D} \tag{2.9}$$

Δ_{cr}can then be converted into the bar radius loss δ_{cr}:

$$\delta_{cr} = \frac{D}{2} - \sqrt{\frac{D^2}{4}\left(1 - \frac{\Delta_{cr}}{100}\right)} \approx 1.25\, c \tag{2.10}$$

The time to cracking is thus given by:

$$t_{cr} = \frac{1000\,\delta_{cr}}{11.6\, I_{corr}} \tag{2.11}$$

Where: c = concrete cover to bar (mm)

D = bar diameter (mm)

I_{corr}= corrosion rate (µA/cm2)

δ_{cr} = bar radial loss required for corrosion-induced cracking (µm)

Δ_{cr}= bar section loss required for corrosion – induced cracking (%)

- **An acceleration period** of damage where corrosion increases due to easy access of oxygen and water through cracks in the cover concrete, resulting in spalling of concrete.

Unfortunately most reinforced concrete structures that exhibit cracking and spalling have gone beyond the point where simple, cost-effective measures can be taken to restore durability. Condition surveys are therefore an important strategy to identify and quantify the state of corrosion of a structure as early as possible.

The consequences of corrosion [13] are many and varied and the effects of these on the safe, reliable and efficient operation of equipment or structures are often more serious than the simple loss of a mass of metal. Failures of various kinds and the need for expensive replacements may occur even though the amount of metal destroyed is quite small.

Some of the major harmful effects of corrosion in structures can be summarizedas follows, [13].

- Reduction of reinforcement thickness leading to loss of mechanical strength and structural failure or breakdown. When the reinforcement is lost in localized zones so as to give a crack like structure, very considerable weakening may result from quite a small amount of metal loss,
- Hazards or injuries to people arising from structural failure or breakdown (e.g. bridges and buildings),
- Reduced value of goods due to deterioration of appearance.

Corrosion of steel in concrete is a serious problem in reinforced concrete structures of the world today. In developed countries one-half of highway bridges are deteriorating due to the corrosion of reinforcement, and billions of dollars are required to repair or rehabilitate the damaged structures, [6].

The following shown in table 2.1, [6],is damages exhibited mainly corrosion resulted defects.

EVENT	DAMAGE	ECONOMIC LOSS	REFERENCES
Estimate in USA	Corrosion damage of highway bridges	$90 ~ $150 billion	Federal Highway Administration
Estimate in USA	Annual cost of repair of bridge deck, substructures and car parks	$200 ~ $450 million	Transportation Research Board
Estimate in UK	Corrosion damage of motor way and trunk road bridges in England and Wales	GBP 616.5 million	Wallband (1989)
Estimate in UK	Annual cost of repairs to concrete structures	GBP 500 million	Rosenberg (1989)
Collapse of the Berlin congress hall	Collapse		Isecke (1982)
Collapse of multistory parking in Minnesota	Collapse		Heidersbach (1986)
Collapse of post-tensioned concrete bridge in Wales	Collapse		Woodward (1988)
Slab spalled of a bridge InNew York	One man killed		Broomfield (1997)

Table 2.1 Damage and economic loss associated with corrosion of steel in concrete

2.7. CORROSION DETECTION IN A BUILT STRUCTURES

A detailed corrosion or condition surveyis vital in order to identify the exact cause and extent of deterioration, before repair options are considered. Corrosion detection methods in built structures are as follows: [9]

2.7.1. VISUAL ASSESSMENT

Corrosion damage may be identified and defined using a systematic visual survey. Classification of visual evidence of deterioration must be done objectively, following clear guidelines that define damage in termsof appearance, location and cause. Defects may be defined in terms of cracks (caused by corrosion, temperature, shrinkage or fatigue), joint deficiencies (joint spalls, upward movement, lateral movement, sealdamage) surface damage (abrasion, rust stains, delamination, spalls), changes in member shape (curling, deflection, settlement, deformation) and textural features (blow holes, honeycombing, sand pockets, segregation).

Visual assessment of deterioration can provide useful information when done in a rational, systematic manner but the data may come too late for cost-effective repairs. Rebar corrosion damage is often only fully manifest at the surface after significant deterioration has occurred. Early evidence of distress can sometimes be detected by an experienced engineer before major distress takes place.

2.7.2.DELAMINATION SURVEY

A hammer survey or chain drag is a simple method of locating areas of delamination in concrete. Hollow sounding areas can be marked up on the concrete or recorded directly in a survey form. Delamination surveys often under-estimate the full extent of internal cracking and should notbe considered as definitive. Radar and ultrasonic instruments may provide a more sophisticated approach to locating areas of delamination, particularly at greater depths.

2.7.3.COVER SURVEYS

Cover surveys are routinely done to locate the position and depth of reinforcement within a concrete structure. Covermeters use an alternating magnetic field to locate steel and any other magnetic material in concrete. Cover measurementsmay be unreliable when:

- rebar is at deep covers (e.g. covers greater than 80 mm)
- measuring regions of closely spaced bars
- measuring differing bar types and sizes (unless specifically calibrated)
- other magnetic material is nearby (e.g. window frames, wire ties, bolts)

To ensure reliable cover depths from a survey, direct measurements of rebar depths should be made by exposing a limited number of bars. Calibration can then be made for site specific conditions such as rebar type, concrete and environmental influences.

2.7.4.CARBONATION DEPTH

Carbonation depth is measured by spraying fresh concrete with a phenolphthalein indicator solution (1% by mass in ethanol/water solution). Phenolphthalein remains clear where concrete is carbonated but turnspink/purple where concrete is still strongly alkaline (pH > 9.0). Carbonation moves through concrete as a distinct front and reduces the natural alkalinity of concrete from a pH in excess of 12.5 to approximately8.3, with a pH level of 10.5 being sufficiently low to depassivatesteel. Environmental conditions most favorable for carbonation (i.e. 50 –65 % R.H.) are usually too dry to allow rapid steel corrosion that normally requires humidity levels above 80% R.H. Structures exposed to fluctuations in moisture conditions of the cover concrete, such as may occur during rainy spells, are however vulnerable to carbonation induced corrosion.

2.8. CORROSION MEASUREMENT IN A BUILT STRUCTURES

It is beneficial to know the extent of corrosion in reinforcing steel in concrete. Currently, there is no instrument/technique available that can measure the extent of corrosion of steel. However, the measurement of concrete properties, such as resistivity and potential of concrete can assess the probability of corrosion of reinforcing steel. Resistivity meter and corrosion analyzing instrument, can measure these properties.

2.8.1.RESISTIVITY

Concrete resistivity controls the rate at which steel corrodes in concreteonce favorable conditions for corrosion exist. Resistivity is dependenton the moisture condition of the concrete, on the permeability and interconnectivityof the pore structure, and on the concentration of ionicspecies in the pore water of concrete such that: [9]

- poor quality, saturated concrete has low resistivity (e.g. less than 10kOhm.cm)
- high quality, dry concrete has high resistivity (e.g. greater than 25kOhm.cm)

Resistivity meter:

The corrosion of steel in concrete is an electro-chemical process that produces a flow of current. Resistivity of the concrete influences the flow of this current. The lower the electric resistance, the more easily corrosion current flow through the concrete and the greater is the probability of corrosion. Therefore, the resistivity of concrete is a good sign of probability of corrosion. The electrical resistance of reinforced concrete components can be measured by resistivity meter. Once the concrete resistivity is known a rough assessment of likely corrosion rates can be made as shown in Table 2.2 This assessment assumes conditions are favorable for corrosion. [9]

RESISTIVELY LEVEL (KILO-OHM / CM)	POSSIBLE CORROSION RATE
< 12	High
12 to 20	Moderate
> 20	Low

Table 2.2 Resistivity level and corrosion rate

Resistivity meter is very handy and portable equipment weighing about 2.2 kg. It has two or more probes, which are placed on concrete surface with conductive gel between probes and surface and the concrete resistivity is shown on a LCD. Recently, resistivity meters are obtainable with non-volatiles memory and colored graphic display from which data can be transferred on to computer.

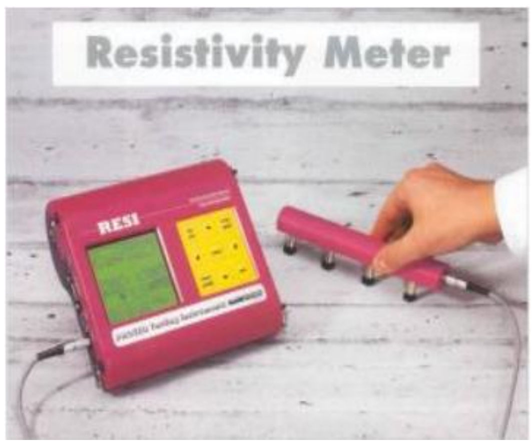

Figure 2.6 Resistivity meter

To measure the resistivity, metallic probes are placed over the concrete surface. A known current is passed on the outer probes and resulting potential drop between inner probes is measured. The resistance is then computed by dividing potential drop by the current. With the help of resistivity meter, probability of corrosion can be assessed. This is a very simple technique and can be adopted easily in the field without and disruption to traffic.

Resistivity measurements are simple to perform on site but have severallimitations:

- Measurements are affected by carbonation and wetting fronts
- Surface conductive layers and rebar directly below the probe shouldbe avoided
- Readings may be unstable in concretes with high contact resistance atthe surface

2.8.2.CORROSION RATE MEASUREMENTS

Corrosion rate measurements are the only reliable method of measuringactual corrosion activity in reinforced concrete. A number of sophisticatedcorrosion monitoring systems are available, based primarily on linearpolarization resistance (LPR) principles. These techniques require considerableexpertise to operate reliably. Corrosion rate measurements onfield structures are most commonly done using galvano-static LPR techniqueswith a guard-ring type sensor to confine the area of steel undertest. Experience indicates that corrosion rates fluctuate significantly inresponse to environmental and material influences and single readingsare generally unreliable. Table 2.3 shows a qualitative guide for the assessmentof corrosion rates of site structures.[9]

CORROSION RATE (μA/CM^2)	QUALITATIVE ASSESSMENT OF CORROSION RATE
>10	High
1.0 – 10	Moderate
0.2 -1.0	Low
< 0.2	Passive

Table 2.3 Qualitative assessment of site corrosion rates

Corrosion analyzing equipment:

Difference in potential between concrete surface and steel is a good indicator of current flow. The electrochemical process produces an electric current, which is measurable as an electric field on the surface of the concrete. This potential field can be measured with an electrode known as half cell. By making measurement over the whole surface, a distinction can be made between likely corroding and non-corroding locations. The probability of corrosion with respect to the values of potential difference is normally considered as given in table below:

POTENTIAL VALUE	POSSIBLE CORROSION RATE
</= 0.20 V	90% probability of no corrosion
0.20 to -0.35 V	Corrosion activity uncertain
> 0.35 V	more than 90% probability of corrosion

Table 2.4 Potential value and possible corrosion rate

Corrosion analyzing instrument is small, handy equipment weighing about 5.5kg with large display and simple operation. Measured values can be represented on the display. Measurements can be stored in the memory. Its data can be transferred to computers.

Figure 2.7 Corrosion analyzing instrument

The steel in concrete structure should be accessible at few locations to provide electrical connection. For new structures, such locations should be decided at the design stage itself. The connections project out of the concrete.

2.8.3.PREDICTION OF SERVICE LIFE BASED ON CORROSION RATE MEASUREMENTS

The measurements of corrosion rate [13] have been used by both Andrade and Clear to estimate the remaining service life of reinforced concrete in which corrosion isthe limiting degradation process. Both models used the polarization resistancetechnique to measure corrosion currents. The Andrade model considers reduction ofthe steel section as the significant consequence of corrosion instead of cracking or spalling of concrete. The corrosion current is converted to reductions in the diameterof reinforcing steel by the following relationship:

$$d(t) = d(0) - 0.023 * Icorr * t \qquad (2.12)$$

Where:

- d(t) = the reinforcement diameter in (mm) at time (t) in years after the beginningof propagation period
- d(0) = the initial diameter of the reinforcement in (mm)
- Icorr= the corrosion rate in ($\mu A/cm^2$)

- 0.023 = the conversion factor of μA/cm^2 into mm/year

Clear based his model on the combination of laboratory, outdoor exposure and fieldstudies. He suggested the use of the following relationships between the corrosionrates and remaining service life:

- Icorr less than 0.5μA/cm^2 (6μm/year) – no corrosion damage expected.
- Icorr between 0.5 and 2.7 μA/cm^2 (6 and 30μm/year) – corrosion damage possible in the range of 10 to 15 years.
- Icorr between 2.7 and 27 μA/cm^2 (30 and 300μm/year) – corrosion damage expected in^2 to 10 years.
- Icorr in excess of 27μA/cm^2 (300μm/year) – corrosion damage expected in 2years or less.

Both models assume the linear change of corrosion rate with time. However, themeasured corrosion rate is changing with time depending on the variations of thetemperature and humidity. To overcome this problem Andrade calculates an averagecorrosion rate over a year. Another way to overcome this problem is the empiricalextrapolation.

2.9. CORROSION CONSIDERATION IN DEVELOPED COUNTRIES

Corrosion of steel rebar is the major cause of concrete deterioration in reinforced and pre-stressed concrete structures. Each year billions of dollars are spent to repair the damages resulting from this type of corrosion that initiates when salts, water and air penetrate through the pores of concrete and reach the surface of the steel. In general, embedded steel rebar in concrete is stable; the concrete provides a highly alkaline, protective environment. Problems arise when the embedded concrete structure is exposed to the aforementioned corrosive species, [3].

The petroleum, chemical, construction, manufacturing, pulp and paper and transportation (railroad, automotive and aerospace) industries are the largest contributors to corrosion expenditure.

The cost of corrosion differs from country to country. For instance in USA, the transportation sector is the largest sector contributing to corrosion after public utilities, whereas in the oil producing countries, such as the Arabian Gulf countries, petroleum and petrochemical industries are the largest contributor to corrosion expenditure. The highway sector in USA alone includes 4,000,000 miles of highways, 583,000 bridges, which need corrosion remediation maintenance.The annual direct corrosion cost estimated to be 8.3 billion US dollars. The direct corrosion of transportation sector is estimated to be 29.7 billion US dollars. It includes the corrosion cost of aircraft, hazardous materials transport, motor vehicles, railroad car and ships, [11].

In a study of corrosion cost conducted jointly by Corrosion Control Technologies Inc., USA, Federal Highway Agencies (FHWA), USA and National Association of Corrosion Engineers, the direct corrosion cost was estimated to be around 276 billion US dollars, approximately 3.1% of the national gross domestic product. Based on an extensive survey conducted by Battelle Columbus Laboratories, Columbus, Ohio, USA and National Institute of Standards and Technology (NIST), in 1975, the cost was estimated to be 82 billion US dollars, which would have exceeded 350 billion US dollars in view of price inflation over the last twenty-five years. Because of the long time involved in conducting cost structure, it is not possible to update the information every year. However, both studies show that corrosion costs are staggering and a figure of about 350 billion US dollars appear to be a reasonable estimate for another two to three years. At least 35% of the above amount could have been saved by taking appropriate corrosion control measures,[11]. Introduction to corrosion

In UK, the corrosion cost is estimated to be 4–5% of the growth national product. In Japan, the cost of corrosion is estimated to be 5258 trillion Yen per year. For most industrialized nations, the average corrosion cost is 3.5–4.5% of the growth national product. Below are some startling figures of corrosion losses: [11]

- Nearly 95% of concrete damage in the Arabian Gulf coastal region is caused by reinforcement corrosion and consequent spalling of concrete.
- Major annual corrosion losses to the tune of £350 million in transport, £280 million in marine, £250 million in buildings and construction and £180 million in oil and chemical industries, have been reported in UK .These are uncorrected 1971 figures.
- About $120 billion is spent on maintenance of aging and deteriorating infrastructures in USA.

From the above summary, it is observed that corrosion exists everywhere and there is no industry or house where it does not penetrate and it demands a state of readiness for engineers and scientists to combat this problem.

3. CORROSION CONSIDERATION IN ETHIOPIAN PRACTICE

As it was clearly described in section 2.8, corrosion is a major concern in developed countries and the people are aware of its damages. Therefore, millions of dollars are spent for maintenance of structures to curb the failing effect of the structures.

In our country, no specific defect identification due to corrosion is used since the method of identification is based on physical observation. As the problem of corrosion essentially produces damage with respect to durability, its effect is not noticed immediately and hence, less importance is given.

Even when a structure fails, suspect of reinforcement corrosion comes at last or may not at all considered as source of damage. The main problem is that people are not aware of the damages caused by reinforcement corrosion.

In the following two sections, the reinforcement corrosion consideration in construction sites and corrosion in already built structures are covered.

3.1. HANDLING OF REINFORCEMENTS

These includecondition of steel handling from the factories up to delivery to site.

3.1.1.FACTORIES

Thereare reinforcement producing companies in our country but these companies do not give instructions on how to handle and store the reinforcements.

3.1.2.TRANSPORTATION

Due to the rapid economic growth of our country, many structures are under construction. Their locations are different and are throughout the country. Due to this, some sites may be far from the factories many kilometers away. To transport these materials, it may take two or three days. As it is known, the trucks carrying the reinforcements do not have covers. As a custom and due to their length, reinforcements are not covered and even it is considered as if it should be transported in that way. Due to this, temperature variation may cause to initiate the reinforcement corrosion. Since carbon dioxide and water are the main causes of corrosion, the process may start during transportation. Sample transportation truck to transport steel is shown in figure 3.1 below.

Figure 3.1 Photograph showing trucks carrying reinforcement bars

3.1.3.STORAGE

Materials shall generally be stored on site in a manner that would prevent damage to the materials. In construction sites, much attention is given on storage of cement. Cement is stored in bags or containers in an enclosed, ventilated space that would protect it from deterioration.

However, reinforcements are not stored as with great care as the cements. They are usually stored in an open area. In our country, it is true that the construction progress of most construction sites is too slow and the reinforcements may be delivered in bulk quantities. As a result, seasons may change in those reinforcements being stored at one place. In fact, in some construction sites some supervisors force the contractors to clean the dirt and also the corrosion materials from the reinforcement surfaces. But this is not done effectively because it is time taking and needs the supervisors'' careful attention. Figures 3.2 to 3.13 represents storage conditions as practiced in most of the sites in our country.

Figure 3.2 Photograph showing storage of reinforcement bar for construction of mixed use building Bambis area, Addis Ababa -1

Figure 3.3 Photograph that shows accumulated reinforcement bars for construction of mixed use building Bambis area, Addis Ababa-2

Figure 3.4 Photograph illustrating mixed use building Bambis area, Addis Ababa – 3

Figure 3.5 Photograph that illustrates railway project around Meskel square, Addis Ababa

Figure 3.6 Photograph showing storage of reinforcement bar for construction of G+3 parking Kazanchis area, Addis Ababa - 1

Figure 3.7 Photograph that shows storage of reinforcement bar for construction of G+3 parking Kazanchis area, Addis Ababa - 2

Figure 3.8 Photograph illustrating storage of reinforcement bar for construction of G+3 parking Kazanchis area, Addis Ababa - 3

Figure 3.9 Photograph that illustrates storage of reinforcement bar for construction of G+3 parking around Kazanchis, Addis Ababa – 4

Figure 3.10 Photograph showing storage of reinforcement bar for construction of G+6 office building around Yerer, Addis Ababa - 1

Figure 3.11 Photograph that shows storage of reinforcement bar for construction of G+6 office building around Yerer, Addis Ababa – 2

Figure 3.12 Photograph demonstrating storage of reinforcement bar for railway project around St. Joseph Church, Addis Ababa

Figure 3.13 Photograph indicating storage of reinforcement bar for a mixed use building around WuhaLimat , Addis Ababa

3.1.4. ACTIVITIES PRIOR TO CASTING OF CONCRETE

Sometimes after the reinforcements are tied at their exact position as per the structural drawing, casting of concrete may delay due to shortage of concrete ingredients, bad weather condition or other cases. Consequently, the reinforcements may be exposed to temperature variations for longer periods.

Reinforcements placed and exposed to rusting on structures under construction may last months and sometimes years are shown in Figure 3.14 – 3.20.

Figure 3.14 Photograph illustrating reinforcements prepared prior to casting of concrete and exposed to various environments mixed use building around Bambis area, Addis Ababa **-1**

Figure 3.15 Photograph that illustrates reinforcements prepared for footing for Railway project around Meskel square, Addis Ababa- 2

Figure 3.16 Photograph showing reinforcements prepared for footing for Railway project around Meskel square, Addis Ababa- 3

Figure 3.17 Photograph that illustrates prepared reinforcement bars prior to casting of concrete at TanaBeles sugar factory, BahirDar

Figure 3.18 Photograph that shows prepared reinforcement bars prior to casting of concrete aroundGerji area, Addis Ababa

Figure 3.19 Photograph that illustrates prepared reinforcement bars prior to casting of concrete at for the new rail way project around St. Joseph Church

Figure 3.20 Photograph that illustrates prepared reinforcement bars prior to casting of concrete around 22 Mazoria, Addis Ababa

3.1.5.POOR CONSTRUCTION METHODS AND WORKMANSHIP

Poor construction methods and workmanship is caused by negligence and inadequate quality control at construction sites. Due to this, poor construction methods and workmanship are responsible for the failure of buildings and structures.

Figure 3.21 People working at construction site

In different construction sites in our country, the effects of some of the poor construction methods are discussed below.

- **INADEQUATE COVER TO REINFORCEMENT**

Most of the time, due to negligence and inadequate quality control, the cover to reinforcement is not properly monitored. The consequence of this permits ingression of moisture, gases and other substances and leads to corrosion of the reinforcement and cracking and spalling of the concrete.

- **POOR COMPACTION**

This is also a result of another poor construction method. If concrete is not appropriately compacted, the result is a portion of porous honeycomb concrete. Hence, the affected part must be cut out and recast. To give a dense, impermeable concrete, a complete compaction is essential.

- **INCORRECT PLACEMENT OF STEEL**

Incorrect placement of steel is occurring in construction sites. This leads to insufficient cover and corrosion of the reinforcements. Collapse can occur when the element is fully loaded if the bars are placed in the wrong position.

- **INCORRECTLY MADE CONSTRUCTION JOINTS**

Poor compaction and lack of preparation are the main faults in construction joints. Poor joints permit ingress of moisture and staining of the concrete face. Before pouring the new concrete, the old one should be washed and a layer of rich concrete must be laid.

- **POOR CURING**

Loss of water through evaporation is a result of poor curing procedure. If there is no sufficient water for complete hydration of the cement, it can cause a reduction in strength and shrinkage cracking. Therefore, during curing the concrete should be kept damp and covered. .

- **TOO HIGH A WATER CONTENT**

Sometimes, in construction sites excess water is added to increase workability but this decreases the concrete strength and leads to increase the porosity and permeability of the concrete. As a result, the reinforcements corrode. Therefore, the correct water to cement ratio for the mix should be strictly enforced.

- **GROUT LEAKAGE**

Due to lack of incorrectly sealed formwork joints, grout leakage occurs. The result is a porous area of concrete that has little or no cement and fine aggregate.

3.2. CORROSION IN ALREADY BUILT STRUCTURES

Already built structures usually have hairline cracks. These cracks may extend larger and become reasons for the formation of corrosion on the reinforcement surfaces.

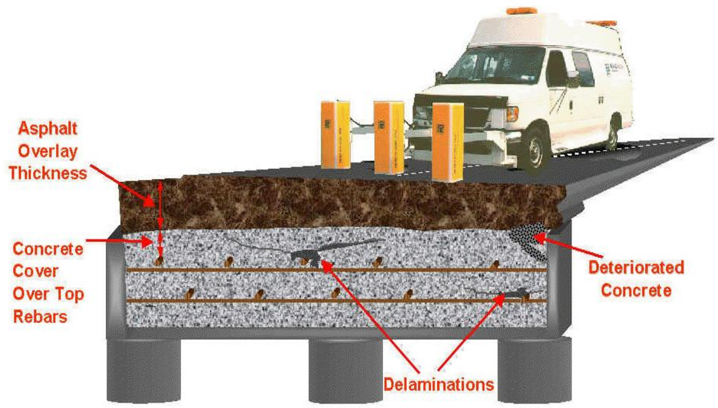

Figure 3.22 Cross-section showing deteriorated concrete, asphalt overlay thickness and concrete cover top re-bars

It is extremely vital in order to protect bridges from any major problem of damage, identification of premature deteriorations.

Understanding of this enables the Ethiopian Roads Authority to effectively use the funds to avoid further deterioration and to take correct measures through proper maintenance and repair, balancing the need for safety as well as to reduce any inconvenience and disruption to travel due to bridge closures or limitations. In order to assist bridge managers to achieve the above-mentioned objectives, establishment of a system is an important issue. This system helps to have bridge information and condition assessment output as well as to decide on the required budget for recommended improvement options. Such a system is called a Bridge Management System (BMS), [14].

A BMS encompasses all engineering and management functions that are necessary to efficiently carry out bridge operations. These include data collection and its management, inspection, planning and programming, construction and maintenance.

The purpose of bridge inspection is to indicate the existing general and detail condition of the bridge in terms of its damage against the proper functionality expected.

A rank of damage to be given for bridge components during inspection indicates the present condition of the bridge. When the given ranks enter in to the computer, the system automatically starts to analyze against the preset weight. As a result we get the extent of bridge damage in terms of damage percent and indication of condition.

These conditions are suggested to be good, fair and bad.

Range of percent for these conditions is also predetermined.

Based on the obtained site inspection result, the Bridges owner can easily decide on rehabilitation matter.

- Good condition – Bridges which are still sound, adequate and functional. These bridges need regular inspection.
- Fair condition – Bridges which are inadequate and require rehabilitation. These bridges need further study and identification of cause for damages. Rehabilitation measure must be decided.
- Bad condition – Bridges which are critical requiring immediate intervention. These bridges need special attention and detail investigation. They may need replacement of damaged bridge parts or whole replacement. Demolishing of the existing bridge, preparation of alternative route and access as well as design of new bridge may be required.

In the following Table 3.1 and figures 3.23 – 3.37, bridges that are in bad condition are shown. The data is collected from Ethiopian Roads Authority bridge management database. The concrete cover peeled off and the reinforcements are exposed to the outside environment, i.e. water and air which made the reinforcement bar to rust. This in-turn leads the reinforcing bars to expand and a certain amount of force was exerted on the concrete cover in the outward direction; this caused the concrete to peel off and additional reinforcement bars exposed. As it is discussed on the previous sections, these conditions play a great role in corrosion of the reinforcement. The cycle repeats itself indefinitely and if left without any intervention it may bring total collapse of the structures and result loss of life.

ETHIOPIAN ROAD AUTHORITY BRIDGE MANAGEMENT TEAM BRIDGE CONDITION

NO	MAIN ROUTE	DISTRICT NAME	ROAD SEGMENT	BRIDGE NAME	KM FROM A.A	BRIDGE LENGTH	BRIDGE TYPE	CONST. YEAR	BRIDGE CONDITION	CURRENT CONDITION
1	Addis-Galafi	Alemgena	Addis-Modjo	Dengora	25.28	10.60	RC Box Culvert	1974	Bad	- Serious crack observed on the deck slab - Cover concrete peel off on the deck slab
2	Addis-Galafi	Alemgena	Addis-Modjo	Ankara	61.86	5.00	RC Slab Culvert	2004	Bad	- Crack, Peel off, Rebar exposure on the deck slab
3	Addis-Galafi	Alemgena	Nazret-Metehara	Denbela	95.50	4.00	RC Slab Culvert	1974	Bad	- Peel off, honey comb
4	Addis-Galafi	Alemgena	Nazret-Metehara	Teteri-Wacho	117.26	12.00	RC Box Culvert	1974	Bad	- Steel deformation
5	Addis-Galafi	Alemgena	Nazret-Metehara	Tami Boba	144.50	4.00	RC Slab Culvert	1974	Bad	- Crack on the deck slab - Rebar exposure and honeycomb
6	Addis-Galafi	Alemgena	Nazret-Metehara	Crasher	157.50	4.00	RC Slab Culvert	1974	Bad	- Rebar exposure and honeycomb
7	Addis-Galafi	Dire Dawa	Awash-Gedamaitu	Oromo	220.50	41.00	RC Deck Girder	1972	Bad	- Bridge deck slab and girders are cracked - Water leakage on the deck slab
8	Addis-Galafi	Dire Dawa	Awash-Gedamaitu	Unknown	252.10	5.00	RC Slab Culvert	1972	Bad	- Severe cracking on the abutment walls & deck slab. Generally, the bridge is at the verge of failure.
9	Addis-Galafi	Dire Dawa	Awash-Gedamaitu	GUDLESI	258.52	12.50	RC Deck Girder	1971	Bad	- Severe cracking on the slab and girder, - water leakage on the slab and abutment walls.

NO	MAIN ROUTE	DISTRICT NAME	ROAD SEGMENT	BRIDGE NAME	KM FROM A.A	BRIDGE LENGTH	BRIDGE TYPE	CONST. YEAR	BRIDGE CONDITIO N	CURRENT CONDITION
10	Addis-Galafi	Dire Dawa	Awash-Gedamaitu	Unknown	313.84	6.35	RC Slab Culvert	1971	Bad	- Serious cracking on the slab - Honey comb showed on the slab
11	Addis-Galafi	Dire Dawa	Gedamaitu-Gewane	GALALO	315.04	9.00	RC Deck Girder	1971	Bad	- Crack on the abutment
12	Addis-Galafi	Dire Dawa	Gedamaitu-Gewane	MINSHADA	345.26	8.00	RC Slab Culvert	1971	Bad	- Crack on deck slab.
13	Addis-Galafi	Dire Dawa	Gedamaitu-Gewane	Unknown	347.65	9.00	RC Slab Culvert	1971	Bad	- Crack on deck slab.
14	Addis-Galafi	Dire Dawa	Gedamaitu-Gewane	Unknown	354.43	10.10	RC Slab Culvert	1971	Bad	- Water leakage on most parts of the joint of girder and diaphragm.
15	Addis-Galafi	Dire Dawa	Gedamaitu-Gewane	Harfte	363.65	17.70	RC Deck Girder	-	Bad	- Water leakage on most parts of the joint of girder and diaphragm. - Severe crack on the Deck Girder, diaphragm and bearing shelf.
16	Addis-Galafi	Dire Dawa	Gewane-Undufu	GEWANE	368.13	22.00	RC Deck Girder	1971	Bad	- Crack and water leakage on deck slab.
17	Addis-Galafi	Dire Dawa	Gewane-Undufu	AMBULE	384.84	41.00	RC Deck Girder	1971	Bad	- Crack and leakage on deck slab.
18	Addis-Galafi	Dire Dawa	Gewane-Undufu	Unknown	403.93	4.50	RC Slab Culvert	-	Bad	- Crack and water leakage on deck slab.
19	Addis-Galafi	Dire Dawa	Gewane-Undufu	Unknown	405.39	4.50	RC Slab Culvert	1971	Bad	- Crack, water leakage and rebar exposure on deck slab.
20	Addis-Galafi	Dire Dawa	Gewane-Undufu	Unknown	407.80	7.00	RC Box Culvert	1971	Bad	- The deck slab, wing wall and abutment undergo severe crack network.

NO	MAIN ROUTE	DISTRICT NAME	ROAD SEGMENT	BRIDGE NAME	KM FROM A.A	BRIDGE LENGTH	BRIDGE TYPE	CONST. YEAR	BRIDGE CONDITIO N	CURRENT CONDITION
21	Addis-Galafi	Dire Dawa	Undufu-Adaitu	Unknown	428.59	4.90	RC Slab Culvert	1974	Bad	- The abutment undergo severe crack from top to bottom.
22	Addis-Galafi	Dire Dawa	Undufu-Adaitu	Unknown	440.10	4.00	RC Slab Culvert	-	Bad	- It has a crack on deck slab.
23	Addis-Galafi	Dire Dawa	Undufu-Adaitu	Unknown	457.86	19.50	RC Deck Girder	1971	Bad	- The desk slab undergoes severe crack network and water leakage. - The concrete girder undergo severe shear crack.
24	Addis-Galafi	Dire Dawa	Undufu-Adaitu	Unknown	472.56	16.70	RC Deck Girder	1971	Bad	- Water leakage on the deck slab.
25	Addis-Galafi	Dire Dawa	Undufu-Adaitu	ELMITGEN	476.86	31.50	RC Deck Girder	1971	Bad	- The deck slab suffers from network crack and water leakage.
26	Addis-Galafi	Dire Dawa	Adaitu-Mille	Unknown	491.31	9.85	RC Slab Culvert	1971	Bad	- This bridge undergoes with a very severe horizontal, vertical and diagonal cracking on the abutment walls.
27	Addis-Galafi	Dire Dawa	Adaitu-Mille	Unknown	495.05	62.25	RC Deck Girder	1971	Bad	- The bridge deck slab and girders are cracked - Rebar exposure on the top of the deck slab
28	Addis-Galafi	Dire Dawa	Adaitu-Mille	GERARU	505.96	61.50	RC Deck Girder	1971	Bad	- Deck slab and girders are cracking that needs repair.
29	Addis-Galafi	Dire Dawa	Adaitu-Mille	WARANSO1	511.16	40.00	RC Deck Girder	1971	Bad	- The Bridge undergoes sever cracking and water leakage on the deck slab.
30	Addis-Galafi	Dire Dawa	Adaitu-Mille	WARANS O2	511.34	41.20	RC Deck Girder	1971	Bad	- Crack on the deck slab and girder of the bridge.

NO	MAIN ROUTE	DISTRICT NAME	ROAD SEGMENT	BRIDGE NAME	KM FROM A.A	BRIDGE LENGTH	BRIDGE TYPE	CONST. YEAR	BRIDGE CONDITION	CURRENT CONDITION
31	Addis-Axum	Adigrat	Maychew-Adigudom	Teklehaimanot	666.81	29.85	RC Deck Girder	1945	Bad	- Crack on deck and girder - Cover concrete peel off and rebar exposure on girder - Water leakage on deck
32	Addis-Axum	Adigrat	Maychew-Adigudom	Gabaat-1	681.70	4.30	RC Slab Culvert	2002	Bad	- Crack & honey comb on the arch - Cover concrete peel off
33	Addis-Axum	Adigrat	Maychew-Adigudom	Atsela	701.63	12.40	RC Deck Girder	1939	Bad	- Peel off, rebar exposure, water leakage & honey comb on deck & girder.
34	Addis-Axum	Adigrat	Maychew-Adigudom	Ayne-Selam	723.92	24.20	RC Deck Girder	2002	Bad	- Honey comb & water leakage on deck slab - Peel off & rebar exposure on girder - Crack on deck
35	Addis-Axum	Adigrat	Maychew-Adigudom	Mai Atewanu	740.57	8.10	RC Deck Girder	1993	Bad	- Honey comb on deck slab and girder - Peel off & rebar exposure on deck - Rebar exposure on Girder
36	Addis-Axum	Adigrat	Adigudom-Mekele	Meskila	762.25	4.00	RC Deck Girder	2003	Bad	- Crack, rebar exposure and water leakage on deck slab
37	Addis-Axum	Adigrat	Adigudom-Mekele	Unknown	772.13	9.00	RC Box Culvert	1990	Bad	- Crack and water leakage on deck slab
38	Addis-Axum	Adigrat	Maychew-Adigudom	Unknown	674.30	4.00	RC Slab Culvert	2002	Bad	- Crack on abutment and deck slab

NO	MAIN ROUTE	DISTRICT NAME	ROAD SEGMENT	BRIDGE NAME	KM FROM A.A	BRIDGE LENGTH	BRIDGE TYPE	CONST. YEAR	BRIDGE CONDITION	CURRENT CONDITION
39	Addis-Axum	Adigrat	Maychew-Adigudom	Gebaat-2	681.10	5.00	RC Deck Girder	2002	Bad	- Crack on deck slab and girder - Rebar exposure ,peel off and honey comb on girder - Honey comb, rebar exposure & peel off on deck slab
40	Addis-Axum	Adigrat	Mekele-Negash	Mai Agula	816.12	8.90	RC Deck Girder	1945	Bad	- Crack on railing
41	Addis-Axum	Adigrat	Mekele-Negash	Unknown	817.32	5.20	RC Box Culvert	1945	Bad	- Crack on deck slab - Concrete cover peel off
42	Addis-Axum	Adigrat	Mekele-Negash	Unknown	821.35	6.00	RC Box Culvert	2002	Bad	- Peel off on deck - Crack on deck slab and pier
43	Addis-Axum	Adigrat	Mekele-Negash	Gereda	822.13	6.00	RC Deck Girder	1940	Bad	- Crack on abutment and girder-Peel off and rebar exposure
44	Addis-Axum	Adigrat	Mekele-Negash	Unknown	822.91	5.00	RC Slab Culvert	1953	Bad	- Crack on girder and deck slab - Peel off & rebar exposure
45	Addis-Axum	Adigrat	Mekele-Negash	Mai-Tseyuk	824.34	6.00	RC Deck Girder	1936	Bad	- Peel off & rebar exposure
46	Addis-Axum	Adigrat	Mekele-Negash	Unknown	825.12	4.00	RC Deck Girder	1954	Bad	- Crack on girder and deck slab - Rebar exposure
47	Addis-Axum	Adigrat	Mekele-Negash	Genfel	828.61	14.80	RC Deck Girder	1945	Bad	- Crack on grider and abutment - Cover concrete spall off and rebar exposed to the outside environment.
48	Addis-Axum	Adigrat	Mekele-Negash	Belesa	832.40	4.00	RC Deck Girder	2002	Bad	- Water leakage
49	Addis-Axum	Adigrat	Negasg-Adigrat	Mai-Ayni	846.99	7.90	RC Deck Girder	1937	Bad	- Crack on abutment - Rebar exposed , water leakage

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50	Addis-Axum	Adigrat	Negasg-Adigrat	Gereb-Gormodo	855.02	12.00	RC Deck Girder	1940	Bad	- Cover concrete peel off & water leakage - Rebar exposure
51	Addis-Axum	Adigrat	Negasg-Adigrat	Bahriyawito	862.47	26.00	RC Deck Girder	1945	Bad	- Crack on the abutment, pier and girder - Rebar exposure, cover concrete peel off and water leakage on the deck and pier
52	Addis-Axum	Adigrat	Negasg-Adigrat	Mai-Gemba	864.68	16.00	RC Deck Girder	1939	Bad	- Crack on the abutment - Rebar exposure, peel off and crack on pier
53	Addis-Axum	Adigrat	Quiha-Maymekden	Dolo	782.87	12.70	RC Deck Girder	1938	Bad	- Peel off on deck slab - Repair exposure, water leakage on the deck slab
54	Addis-Axum	Adigrat	Quiha-Maymekden	Unknown	772.00	4.00	RC Deck Girder	1938	Bad	- Crack on deck slab - Cover concrete peel off
55	Addis-Axum	Adigrat	Adigrat-Bizet	Mai-Kokho	900.22	22.80	PC Deck Girder	1945	Bad	- Deck slab crack & rebar exposure - Water leakage on the deck slab,
56	Addis-Axum	Adigrat	Adigrat-Bizet	MehtsabAlabu	901.00	21.20	RC Deck Girder	1945	Bad	- Crack on the deck slab - Rebar exposure & peel of concrete cover on the girder
57	Addis-Axum	Adigrat	Adigrat-Bizet	Unknown	901.50	5.00	RC Deck Girder	1953	Bad	- Honey comb on the deck slab - Rebar exposure & cover concrete peel off on the girder
58	Addis-Axum	Adigrat	Adigrat-Bizet	Andel	910.80	8.00	RC Deck Girder	1937	Bad	- Crack on deck slab - Cover concrete peel off & rebar exposed

NO	MAIN ROUTE	DISTRICT NAME	ROAD SEGMENT	BRIDGE NAME	KM FROM A.A	BRIDGE LENGTH	BRIDGE TYPE	CONST. YEAR	BRIDGE CONDITIO N	CURRENT CONDITION
59	Addis-Axum	Adigrat	Adigrat-Bizet	Unknown	911.80	5.50	RC Deck Girder	1938	Bad	- Crack on the deck slab and girder
60	Addis-Axum	Adigrat	Adigrat-Bizet	Mai-Mehadaruha	912.27	8.00	RC Deck Girder	1938	Bad	- Cover concrete peel off and rebar exposure on deck slab
61	Addis-Axum	Adigrat	Adigrat-Bizet	Unknown	913.40	5.20	RC Deck Girder	1953	Bad	- Cover concrete peel off and rebar exposure on deck slab
62	Addis-Axum	Adigrat	Adigrat-Bizet	Tselim-Ela	938.30	14.60	RC Deck Girder	1937	Bad	- Crack on Girder and deck
63	Addis-Axum	Adigrat	Adigrat-Bizet	Mai-Meha	939.21	6.00	RC Deck Girder	1940	Bad	- Crack and water leakage
64	Addis-Axum	Adigrat	Bizet - Adiabun	Mengas	940.00	6.80	RC Deck Girder	1938	Bad	- Cover concrete peel off and rebar exposure on deck slab
65	Addis-Axum	Adigrat	Bizet - Adiabun	Mai-Mala	946.00	6.00	RC Deck Girder	1939	Bad	- Cover concrete peel off and rebar exposure on deck slab
66	Addis-Axum	Adigrat	Bizet - Adiabun	Werwer	941.00	14.90	RC Deck Girder	1938	Bad	- Cover concrete peel off on deck and rebar exposed - Water leakage
67	Addis-Axum	Adigrat	Bizet - Adiabun	Mai-Gas	952.64	6.00	RC Deck Girder	1938	Bad	- Water leakage
68	Addis-Axum	Adigrat	Bizet - Adiabun	Unknown	954.90	6.00	RC Slab Culvert	1940	Bad	- Cracking at pier and deck slab - Rebar exposure
69	Addis-Axum	Adigrat	Bizet - Adiabun	Mai-Gebeta	955.95	10.00	RC Slab Culvert	1945	Bad	- Cracking on the deck slab - Peel off head wall and re-bar exposure
70	Addis-Axum	Adigrat	Bizet - Adiabun	Mai-Korich	965.45	7.00	RC Deck Girder	1939	Bad	- Peel off at the head wall - Rebar exposure and water leakage

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71	Addis-Axum	Adigrat	Bizet - Adiabun	Unknown	968.00	5.00	RC Deck Girder	1940	Bad	- Water leakage and rebar exposure
72	Addis-Axum	Adigrat	Bizet - Adiabun	Unknown	968.20	5.00	RC Deck Girder	1940	Bad	- Cracking and rebar exposure
73	Addis-Axum	Adigrat	Bizet - Adiabun	Unknown	973.60	5.10	RC Deck Girder	1940	Bad	- Water leakage and rebar exposure
74	Addis-Axum	Adigrat	Bizet - Adiabun	Mai-Meka	975.30	6.00	RC Deck Girder	1940	Bad	- Rebar exposure on deck slab
75	Addis-Axum	Adigrat	Bizet - Adiabun	Mai-Edega	979.00	6.50	RC Deck Girder Main and-RC Slab Culvert approach	2000	Bad	- Cover concrete peel off and water leakage - Rebar exposure
76	Addis-Axum	Adigrat	Bizet - Adiabun	Unknown	980.42	4.20	RC Deck Girder	1940	Bad	- Peel off on the edge deck slab and water leakage - Rebar exposure
77	Addis-Axum	Adigrat	Bizet - Adiabun	Mai-Daro	992.30	7.00	RC Deck Girder	1938	Bad	- Peel off and water leakage
78	Addis-Axum	Adigrat	Bizet - Adiabun	Unknown	993.57	6.20	RC Deck Girder	1940	Bad	- Water leakage
79	Addis-Axum	Adigrat	Bizet - Adiabun	Unknown	995.77	5.00	RC Deck Girder Main and-RC Slab Culvert approach	1940	Bad	- Rebar exposure on deck slab and head wall
80	Addis-Axum	Adigrat	Adigrat-Bizet	Unknown	907.25	4.80	RC Slab Culvert	2000	Bad	- Crack on the deck slab and girder - cover concrete peel off and rebar exposed
81	Addis-Axum	Adigrat	Adigrat-Bizet	Unknown	912.41	5.00	RC Deck Girder	1940	Bad	- crack and cover concrete peel off
82	Addis-Axum	Adigrat	Adigrat-Bizet	Unknown	935.47	10.00	RC Arch	1937	Bad	- Crack on deck slab

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83	Addis-Axum	Adigrat	Alemata -Moheny-Maychew	Unknown	603.60	6.75	RC Box Culvert	2001	Bad	- Crack on deck slab and peel off - Honey comb on abutment and wing wall - water leakage
84	Addis-Axum	Adigrat	Alemata -Moheny-Maychew	Unknown	610.39	8.75	RC Box Culvert	2001	Bad	- Crack, water leakage and honey comb on deck slab - Peel off on abutment and wing wall
85	Addis-Axum	Adigrat	Alemata -Moheny-Maychew	Gereb-Haya	632.51	30.00	RC Deck Girder	2001	Bad	- Crack on deck slab and girder - Honey comb on girder - Peel off and rebar exposure on curb and railing
86	Addis-Axum	Adigrat	Moheny-Hewane	Burka	657.03	20.00	RC Deck Girder	1999	Bad	- Cracking and Peel of deck slab - Honey comb and rebar exposure
87	Addis-Axum	Adigrat	Waja-Maychew	Horosha-2	590.20	36.00	RC Deck Girder	2003	Bad	- Crack on deck and Girder - Honey comb on Girder
88	Addis-Axum	Adigrat	Waja-Maychew	Gereboda	594.94	24.00	RC Deck Girder	2003	Bad	- Crack on deck slab and Girder
89	Addis-Axum	Adigrat	Waja-Maychew	GerebGando	620.35	12.00	RC Deck Girder	1945	Bad	- Peel off and rebar exposure on deck slab - Water leakage
90	Addis-Axum	Adigrat	Waja-Maychew	Mai Bekolewu	650.24	6.30	RC Slab Culvert	1945	Bad	- Crack on Girder - Honey comb & rebar on deck slab - Rebar exposure & honey comb on Girder
91	Addis-Axum	Combolcha	Haiq- Wuchalie	Weletie	449.22	10	RC Box Culvert	2009	Bad	- Crack on the deck slab
92	Addis-Axum	Combolcha	Robit-Wajja	Gobu	582.60	28.05	RC Box Culvert	2003	Bad	

NO	MAIN ROUTE	DISTRICT NAME	ROAD SEGMENT	BRIDGE NAME	KM FROM A.A	BRIDGE LENGTH	BRIDGE TYPE	CONST. YEAR	BRIDGE CONDITION	CURRENT CONDITION
										- Crack on the deck slab
93	Addis-Axum	Alemgena	Addis - Aleltu	Beke Tributary	41.65	10	RC Arch	1940	Bad	- Peel off on the foundation - Crack on the wing wall
94	Addis-Axum	Alemgena	Addis - Aleltu	Dargie	44.79	5	RC Slab Culvert	2008	Bad	- Honey comb, water leakage and cover peel off on deck slab
95	Addis-Axum	Alemgena	Aleltu - Sembo	Kumite	57.34	10.6	RC Arch	1940	Bad	- Severe crack on the arch part of deck slab - Peel off, honey comb and voids on the arch - Crack , Peel off on the wing wall - Peel off and crack on the railing
96	Addis-Axum	Alemgena	Aleltu - Sembo	Kumite 1	58.27	8.6	RC Slab Culvert	1939	Bad	- Severe peel off, rebar exposure and voids on the deck slab - Honey comb on the deck slab
97	Addis-Axum	Alemgena	Aleltu - Sembo	Sengabelu	60.05	34.4	RC Slab Culvert	1940	Bad	- Scouring on the foundation - Crack on the arch
98	Addis-Axum	Alemgena	Aleltu - Sembo	LegeDuba	65.52	10	RC Deck Girder		Bad	- Severe Crack, Peel off and voids and rebar exposure on the deck slab - Crack, Honey comb and voids on the girder - Crack and peel off on the wing wall.
99	Addis-Axum	Alemgena	Aleltu - Sembo	Legadima	69.50	7.6	RC Slab Culvert	1982	Bad	- Water leakage on the deck - Voids and crack on the deck slab

NO	MAIN ROUTE	DISTRICT NAME	ROAD SEGMENT	BRIDGE NAME	KM FROM A.A	BRIDGE LENGTH	BRIDGE TYPE	CONST. YEAR	BRIDGE CONDITION	CURRENT CONDITION
100	Addis-Axum	Alemgena	Aleltu - Sembo	Angolola	87.90	4	RC Slab Culvert	1994	Bad	- Crack, peel off, Honey comb Voids and water leakage on the deck slab - Rebar exposure
101	Addis-Axum	Alemgena	Aleltu - Sembo	Beressa	88.63	4	RC Slab Culvert	1994	Bad	- Crack, peel off, Honey comb and Voids on the deck - Rebar exposure on the deck
102	Addis-Axum	Alemgena	DebreBerhan - Gudoberet	Derek Wenz	152.90	5	RC Slab Culvert	1938	Bad	- Honey comb and water leakage on the deck slab
103	Addis-Axum	Alemgena	DebreBerhan - Gudoberet	Unknown	154.78	5	RC Slab Culvert	1938	Bad	- Water Leakage on the deck slab
104	Addis-Axum	Alemgena	DebreBerhan - Gudoberet	GoleWenz(Tosignamba)	156.30	5	RC Slab Culvert	1937	Bad	- Water Leakage on the deck slab
105	Addis-Axum	Alemgena	Robit - Awash	Behnsa	253.04	6	RC Slab Culvert	1973	Bad	- Severe peel off, rebar exposure and voids on the deck slab - Steel deformation
106	Addis-Gonder	Debre Markos	Abay River - Degen	Abay No 3(HAILE SILASIE)	206.08	204.45	RC Arch main and RCDG Approach	1947	Bad	- Crack on deck slab and girder - Crack on kerb& railing - Rebar exposure on the deck slab
107	Addis-Gonder	Debre Markos	Abay River - Degen	Abay No 6 - Hidasie	206.08	303.00	RC Box Girder	2008	Bad	- Crack on kerb& railing - Crack on pier & foundation
108	Addis-Gonder	Debre Markos	Abay River - Degen	Denbza Mariam	521.22	9.60	RC Slab Culvert	1947	Bad	- Deck crack & water leakage - Water leakage on expansion joint

NO	MAIN ROUTE	DISTRICT NAME	ROAD SEGMENT	BRIDGE NAME	KM FROM A.A	BRIDGE LENGTH	BRIDGE TYPE	CONST. YEAR	BRIDGE CONDITION	CURRENT CONDITION
109	Addis-Gonder	Debre Markos	Lumame-D/Markos	Zeeba	270.39	10.20	RC Deck Girder	1990	Bad	- Crack and rebar exposure on deck slab - Honey comb and water leakage
110	Addis-Gonder	Debre Markos	Lumame-D/Markos	Godesudit	282.85	4.00	RC Slab Culvert	1945	Bad	- Water leakage on deck slab
111	Addis-Gonder	Debre Markos	Lumame-D/Markos	Useta	290.02	12.20	RC Deck Girder	1990	Bad	- Honey comb and water leakage on girder
112	Addis-Gonder	Debre Markos	Lumame-D/Markos	Kook	273.23	4.00	RC Slab Culvert	1947	Bad	- Peel off & rebar exposure on deck slab
113	Addis-Gonder	Debre Markos	Dber Markos-Denbecha	Wefchobete	312.66	6.20	RC Slab Culvert	1945	Bad	- Crack on deck slab - Peel of cover concrete & rebar exposure on deck slab - Honey comb on deck slab
114	Addis-Gonder	Debre Markos	Dber Markos-Denbecha	Aguatwuha	336.22	10.20	RC Deck Girder	1970	Bad	- Water leakage on deck slab and girder - Crack on girder
115	Addis-Gonder	Debre Markos	Dber Markos-Denbecha	Temcha	337.26	39.00	RC Deck Girder	2001	Bad	- Water leakage on girder and abutment
116	Addis-Gonder	Debre Markos	Dber Markos-Denbecha	Tmbadbad	338.00	8.10	RC Deck Girder	1970	Bad	- Honey comb on girder & deck slab - Water leakage on deck slab - Rebar exposure on girder & deck slab
117	Addis-Gonder	Debre Markos	Dber Markos-Denbecha	Gula	341.35	26.80	RC Deck Girder	1970	Bad	- Expansion joint and water leakage - Rebar exposure on girder
118	Addis-Gonder	Debre Markos	Denbecha-Bure	YecherekaWenz	350.23	13.50	RC Box Culvert	2001	Bad	- Water leakage on abutment - Crack on deck & pier

NO	MAIN ROUTE	DISTRICT NAME	ROAD SEGMENT	BRIDGE NAME	KM FROM A.A	BRIDGE LENGTH	BRIDGE TYPE	CONST. YEAR	BRIDGE CONDITION	CURRENT CONDITION
119	Addis-Gonder	Debre Markos	Denbecha-Bure	LezaWenz	367.36	14.90	RC Deck Girder	1970	Bad	- Honey comb, rebar exposure and peel off on girder
120	Addis-Gonder	Debre Markos	Denbecha-Bure	Jemin	369.69	14.90	RC Deck Girder	1970	Bad	- Honey comb on girder & deck slab - Cover concrete peel off & rebar exposure - Water leakage on the deck slab
121	Addis-Gonder	Debre Markos	Denbecha-Bure	LahWnz	375.39	23.90	RC Arch	1945	Bad	- Crack, honeycomb & peel off on arch - Honey comb, water leakage & void on deck slab - Rebar exposure on Girder & deck slab
122	Addis-Gonder	Debre Markos	Denbecha-Bure	Arerawenz	377.55	11.90	RC Arch	1945	Bad	- Crack on arch - Honey comb & void on arch - Rebar exposure & water leakage on arch
123	Addis-Gonder	Debre Markos	Denbecha-Bure	Gewsa	390.17	10.50	RC Deck Girder	1970	Bad	- Water leakage on girder and expansion joint - Crack & water leakage on the deck slab
124	Addis-Gonder	Debre Markos	Bure-Kossober	Kakess	418.31	13.90	RC Deck Girder	2000	Bad	- Void on deck slab
125	Addis-Gonder	Debre Markos	Dangle-Merawi	Abaytinishu(Pikolo)	498.07	85.20	RC Deck Girder	1945	Bad	- Crack on deck slab & girder - Peel off & rebar exposure on kerb& railing - Rebar exposure, honey comb & water leakage on deck slab - Rebar exposure on pier & foundation - Water leakage on girder

NO	MAIN ROUTE	DISTRICT NAME	ROAD SEGMENT	BRIDGE NAME	KM FROM A.A	BRIDGE LENGTH	BRIDGE TYPE	CONST. YEAR	BRIDGE CONDITION	CURRENT CONDITION
126	Addis-Gonder	Debre Markos	Dangle-Merawi	koga	499.02	12.00	RC Deck Girder	1970	Bad	- Honey comb on girder - Rebar exposure & peel off on girder - Water leakage & honey comb on deck
127	Addis-Gonder	Debre Markos	Merawi-B/Dar	Gudo bahir2	545.27	9.60	RC Box Culvert	2003	Bad	- Crack & water leakage on deck slab - Void on deck slab - Void on abutment & wing wall
128	Addis-Gonder	Debre Markos	Merawi-B/Dar	Gudobahir	545.48	13.50	RC Box Culvert	2003	Bad	- Crack & water leakage on deck slab - Void on deck slab
129	Addis-Gonder	Debre Markos	Merawi-B/Dar	Abay No 4	552.63	149.00	RC Deck Girder	1945	Bad	- Crack, honey comb & peel off on girder - Rebar exposure on girder - Water leakage on deck slab and girder
130	Addis-Gonder	Gonder	Bhairdar- Wereta	Chembel-01	555.51	6.4	RC Slab Culvert	2005	Bad	- Water leakage and cracking on deck slab - Void on deck slab
131	Addis-Gonder	Gonder	Bhairdar- Wereta	Chembel-03	555.55	6	RC Slab Culvert	2005	Bad	- Water leakage on joints
132	Addis-Gonder	Gonder	Bhairdar- Wereta	Yegasho	565.03	15	RC Deck Girder	2005	Bad	- Head wall cracking - Water leakage on girder
133	Addis-Gonder	Gonder	Bhairdar- Wereta	Yedemo-01	567.22	9	RC Slab Culvert	2005	Bad	- Honey comb & water leakage on deck slab

NO	MAIN ROUTE	DISTRICT NAME	ROAD SEGMENT	BRIDGE NAME	KM FROM A.A	BRIDGE LENGTH	BRIDGE TYPE	CONST. YEAR	BRIDGE CONDITIO N	CURRENT CONDITION
134	Addis-Gonder	Gonder	Bhairdar- Wereta	Galda	573.40	45	RC Deck Girder	2005	Bad	- Water leakage and crack on deck slab
135	Addis-Gonder	Gonder	Bhairdar- Wereta	Shoblie	588.00	7.2	RC Slab Culvert	2005	Bad	- Void on deck slab
136	Addis-Gonder	Gonder	Bhairdar- Wereta	Unknown	590.60	12	RC Box Culvert	2005	Bad	- Cracking on foundation
137	Addis-Gonder	Gonder	Bhairdar- Wereta	Boaza-2	592.32	12	RC Box Culvert	2005	Bad	- Water leakage on deck slab
138	Addis-Gonder	Gonder	Bhairdar- Wereta	Gumara	593.55	48	RC Deck Girder	1980	Bad	- Honey comb on deck slab - Joint failure
139	Addis-Gonder	Gonder	Bhairdar- Wereta	Unknown	594.00	18	RC Box Culvert	2005	Bad	- Water leakage
140	Addis-Gonder	Gonder	Bhairdar- Wereta	Unknown	594.17	18	RC Box Culvert	2005	Bad	- Honey comb & water leakage on deck slab
141	Addis-Gonder	Gonder	Bhairdar- Wereta	Unknown	594.35	20	RC Box Culvert	2005	Bad	- Water leakage on deck slab - Void on arch
142	Addis-Gonder	Gonder	Bhairdar- Wereta	Erza	604.85	15	RC Box Culvert	2005	Bad	- Water leakage and cracking on deck slab - Void on deck - Rebar exposure
143	Addis-Gonder	Gonder	Bhairdar- Wereta	Tishkena-1	607.60	6	RC Box Culvert	1965	Bad	- Water leakage on deck slab - Void on slab - Honey comb on deck slab
144	Addis-Gonder	Gonder	Bhairdar- Wereta	Yenevo-02	565.84	4.5	RC Slab Culvert	1965	Bad	- Water leakage - Void on deck slab
145	Addis-Gonder	Gonder	Wereta- Maksegnet	Reb	614.30	48	RC Deck Girder	1962	Bad	- Cracking on expansion joint - Water leakage

NO	MAIN ROUTE	DISTRICT NAME	ROAD SEGMENT	BRIDGE NAME	KM FROM A.A	BRIDGE LENGTH	BRIDGE TYPE	CONST. YEAR	BRIDGE CONDITIO N	CURRENT CONDITION
146	Addis-Gonder	Gonder	Wereta- Maksegnet	Sheni-01	616.30	12	RC Box Culvert	2005	Bad	- Cracking and peel off on deck slab
147	Addis-Gonder	Gonder	Wereta- Maksegnet	Wembweha	650.69	12	RC Deck Girder	1970	Bad	- Water leakage and cracking on expansion joint
148	Addis-Gonder	Gonder	Wereta- Maksegnet	Unknown	665.30	4.1	RC Slab Culvert	2005	Bad	- Cover concrete peel off and water leakage
149	Addis-Gonder	Gonder	Wereta- Maksegnet	Kulkual Ber-2	665.90	4	RC Slab Culvert	2005	Bad	- Water leakage - Peel off on deck slab
150	Addis-Gonder	Gonder	Wereta- Maksegnet	Gumara	682.75	24	RC Slab Culvert	2011	Bad	- Cracking, water leakage and peel off on deck slab
151	Addis-Gonder	Gonder	Maksegnet - AirPort Junction	Agam	684.95	4.2	RC Slab Culvert	2005	Bad	- Void on deck
152	Addis-Gonder	Gonder	Maksegnet - AirPort Junction	Angacha	697.94	10	RC Deck Girder	1988	Bad	- Crack on deck - Water leakage
153	Addis-Gimbi	Alemgena	Holeta - Ginchi	Welonkomi	63.34	11.85	RC Deck Girder	1940	Bad	- Rebar exposure on girder - Cover concrete peel off
154	Addis-Gimbi	Alemgena	Holeta - Ginchi	Batu No 1	70.27	19.5	RC Deck Girder	1975	Bad	- Peel off and honey comb - Rebar exposure
155	Addis-Gimbi	Alemgena	Holeta - Ginchi	Batu No 2	70.72	18.5	RC Deck Girder	1939	Bad	- Rebar exposure and peel off
156	Addis-Gimbi	Alemgena	Holeta - Ginchi	Fekere 2nd	71.01	10	RC Deck Girder	1939	Bad	- Rebar exposure and peel off
157	Addis-Gimbi	Alemgena	Holeta - Ginchi	Unknown	71.11	17.5	RC Deck Girder	1975	Bad	- Rebar exposure and peel off
158	Addis-Gimbi	Alemgena	Ginchi - Ambo	Gurara	77.71	6.8	RC Deck Girder	2004	Bad	- Honey comb - Rebar exposure & peel off
159	Addis-Gimbi	Alemgena	Ginchi - Ambo	Horabila	86.86	22	RC Deck Girder	1939	Bad	- Rebar exposure

NO	MAIN ROUTE	DISTRICT NAME	ROAD SEGMENT	BRIDGE NAME	KM FROM A.A	BRIDGE LENGTH	BRIDGE TYPE	CONST. YEAR	BRIDGE CONDITION	CURRENT CONDITION
160	Addis-Gimbi	Alemgena	Ginchi - Ambo	Horabila	87.45	20	RC Deck Girder	1940	Bad	- Rebar exposure on girder - Cover concrete peel off
161	Addis-Gimbi	Alemgena	Ginchi - Ambo	Quribe	89.61	24	RC Deck Girder	1982	Bad	- Honey comb - Rebar exposure
162	Addis-Gimbi	Alemgena	Ginchi - Ambo	Meti	90.44	20	RC Deck Girder	1938	Bad	- Honey comb & peel off
163	Addis-Gimbi	Alemgena	Ginchi - Ambo	Awaroo	105.57	12	RC Deck Girder	1939	Bad	- Honey comb and rebar exposure
164	Addis-Gimbi	Alemgena	Ginchi - Ambo	Shatafag	107.50	32	RC Slab Culvert	1982	Bad	- Crack & rebar exposure on girder
165	Addis-Gimbi	Alemgena	Ambo - Gedo	Berodo	145.20	10	RC Deck Girder	1940	Bad	- Rebar exposure & honey comb
166	Addis-Gimbi	Nekempt	Gedo - Bako	Bildima	202.69	10	RC Arch	1945	Bad	- Honey comb on deck slab - Water leakage on deck slab
167	Addis-Gimbi	Nekempt	Bako - Nekempt	Gibie	238.36	21	RC Deck Girder	1945	Bad	- Crack on girder - Rebar exposure
168	Addis-Gimbi	Nekempt	Bako - Nekempt	Shucka-2	290.48	10	RC Arch	1937	Bad	- Crack on deck slab
169	Addis-Gimbi	Nekempt	Nekemte-Ephrem	Dhapho	368.99	9	RC Slab Culvert	2002	Bad	- Crack damage
170	Addis-Gimbi	Nekempt	Ephrem-Mekenajo	Dedessa	383.97	82	RC Deck Girder	1959	Bad	- Cracking and water leakage
171	Addis-Gimbi	Nekempt	Ephrem-Mekenajo	Birhirsa	390.55	4.5	RC Slab Culvert	2003	Bad	- Water leakage on honey comb - Cover concrete peel off
172	Addis-Gimbi	Nekempt	Ephrem-Mekenajo	Tolle	393.57	48	RC Deck Girder	1959	Bad	- Water leakage on deck slab
173	Addis-Gimbi	Nekempt	Ephrem-Mekenajo	Unknown	394.93	5	RC Box Girder	2003	Bad	- Cracking and water leakage on deck slab

NO	MAIN ROUTE	DISTRICT NAME	ROAD SEGMENT	BRIDGE NAME	KM FROM A.A	BRIDGE LENGTH	BRIDGE TYPE	CONST. YEAR	BRIDGE CONDITION	CURRENT CONDITION
174	Addis-Gimbi	Nekempt	Ephrem-Mekenajo	Chekorsa	398.90	21	RC Deck Girder	1967	Bad	- Honey comb and water leakage on the deck slab
175	Addis-Gimbi	Nekempt	Ephrem-Mekenajo	Burele	400.64	8	RC Box Girder	2003	Bad	- Honey comb and water leakage on the deck slab
176	Addis-Gimbi	Nekempt	Ephrem-Mekenajo	Bullene	403.65	38	RC Deck Girder	1959	Bad	- Water leakage on the deck slab
177	Addis-Gimbi	Nekempt	Ephrem-Mekenajo	BULULE	404.76	18.8	PC Deck Girder	1967	Bad	- Water leakage on the deck slab
178	Addis-Gimbi	Nekempt	Ephrem-Mekenajo	Gee	416.40	9	RC Box Culvert	1967	Bad	- Cover concrete peel off - Water leakage on the deck slab
179	Addis-Gimbi	Nekempt	Ephrem-Mekenajo	Metti	420.74	8.6	RC Box Culvert	2003	Bad	- Cracking & Water leakage on deck slab
180	Addis-Gimbi	Nekempt	Ephrem-Mekenajo	Gelele	430.45	16	RC Deck Girder	1967	Bad	- Expansion joint peel off
181	Addis-Gimbi	Nekempt	Ephrem-Mekenajo	Melkie	437.05	4.2	RC Slab Culvert	1967	Bad	- Crack on the deck slab
182	Addis-Gimbi	Nekempt	Ephrem-Mekenajo	Melkawala	438.30	6.1	RC Box Culvert	1907	Bad	- Crack & water leakage on deck slab - Crack on the joint
183	Addis-Gimbi	Nekempt	Ephrem-Mekenajo	Gefere	443.16	8.8	RC Box Culvert	1967	Bad	- Crack and honey comb on the deck slab
184	Addis-Gimbi	Nekempt	Ephrem-Mekenajo	Gebie	446.46	6.2	RC Box Culvert	2003	Bad	- Crack and water leakage - Honey comb
185	Addis-Metu	Alemgena	Addis - Tulubolo	Alemgena	20.10	8	RC Deck Girder	1979	Bad	- Water leakage & honey comb on the deck slab

NO	MAIN ROUTE	DISTRICT NAME	ROAD SEGMENT	BRIDGE NAME	KM FROM A.A	BRIDGE LENGTH	BRIDGE TYPE	CONST. YEAR	BRIDGE CONDITION	CURRENT CONDITION
186	Addis-Metu	Alemgena	Welkite - Gibe River	Bokotha	176.66	4	RC Slab Culvert	1939	Bad	- Crack and honey comb on the deck slab
187	Addis-Metu	Jimma	Gibe - Saja	GIBE	185.60	118	RC Deck Girder	1983	Bad	- There is Honeycomb and water leakage on the girder and deck slab. - Voids on the girder and pier
188	Addis-Metu	Jimma	Gibe - Saja	Shankella	186.33	9	RC Slab Culvert	1940	Bad	- Rebar exposure on the deck slab - Minor voids and honey combs on the deck Slab
189	Addis-Metu	Jimma	Assendabo-Jimma	Harare	310.04	7.3	RC Deck Girder	1975	Bad	- On the deck slab of the bridge – Honeycomb and Water leakage - On the Girder of the bridge – Honeycomb - On the Diaphragm(Crossing Girder)- Honeycomb
190	Addis-Metu	Jimma	Agaro - Dedessa river bridge	Dogaja	402.98	12	RC Slab Culvert	1962	Bad	- Water leakage and honeycomb on the deck slab
191	Addis-Metu	Jimma	Agaro - Dedessa river bridge	Tuge	404.24	4	RC Slab Culvert	1962	Bad	- Cracking, Honeycomb and water leakage on the deck slab - Cracking and water leakage on the abutment and wing wall
192	Addis-Metu	Jimma	Agaro - Dedessa river bridge	Semma	414.15	4.5	RC Slab Culvert	1968	Bad	- Major cracks, honeycombs and Water leakage on the deck - Crackings on abutment &wing wall

NO	MAIN ROUTE	DISTRICT NAME	ROAD SEGMENT	BRIDGE NAME	KM FROM A.A	BRIDGE LENGTH	BRIDGE TYPE	CONST. YEAR	BRIDGE CONDITION	CURRENT CONDITION
193	Addis-Metu	Jimma	Agaro - Dedessa river bridge	Gore	422.37	4.5	RC Slab Culvert	1962	Bad	- Major cracking and minor honeycomb on the deck slab - Cracking on the abutment and wing wall of the bridge
194	Addis-Metu	Jimma	Agaro - Dedessa river bridge	Dedessa	433.49	65.6	RC Deck Girder	1970	Bad	- Cracking and honeycomb on the concrete girder - Water leakage through the expansion joint
195	Addis-Metu	Jimma	Chora - Yayu	GEBA	545.26	80	RC Deck Girder	1970	Bad	- Shear cracks on the girder - Bearing is displaced and rusted
196	Addis-Metu	Jimma	Chora - Yayu	BIRBIR	556.63	6	RC Box Culvert	1968	Bad	- Cracks with water leakage on both the deck and abutment
197	Addis-Metu	Jimma	Chora - Yayu	SARI	559.20	5	RC Box Culvert	1968	Bad	- A continuous crack with water leakage on the deck and abutment - Pier cracks with water leakage are observed.
198	Addis-Metu	Jimma	Chora - Yayu	DOGI	566.83	68	RC Deck Girder	1971	Bad	- On girder shear and flexural cracks are observed - Expansion joints are failed - When traffic passes through the bridge, a vibration is felt
199	Addis-Metu	Jimma	Yayu - Metu	GEYI	609.26	4	RC Box Culvert	1968	Bad	- Cracks with water leakage on the deck slab - A continuous crack on the abutment - Voids, honeycomb, and rebar exposure on the deck slab

NO	MAIN ROUTE	DISTRICT NAME	ROAD SEGMENT	BRIDGE NAME	KM FROM A.A	BRIDGE LENGTH	BRIDGE TYPE	CONST. YEAR	BRIDGE CONDITION	CURRENT CONDITION
200	Jimma-Mizanteferi	Jimma	Bonga-Shishinda	Haba	507.68	20	RC Slab Culvert	2011	Bad	- Water leakage on abutment - Honey comb and Water leakage on the deck slab
201	Modjo-Arbaminch	Shasheme ne	Zeway - Shashemene	Shorima	227.20	9.6	RC Deck Girder	1954	Bad	- Water leakage on abutment - Honey comb and Water leakage on the deck slab

Table 3.1 Bridge data

- **BRIDGE NAME - <u>GEWANE</u>**

  Main Route – Addis Galafi

  **District Name - ** Dire Dawa

  Road Segment - Gewane-Undufu**Bridge Type** – RC Deck Girder

  Bridge Length – 22m

  Total Damage – 36.07%

  Current condition - Crack and water leakage on deck slab

Figure 3.23 Crack and water leakage on deck slab

- **BRIDGE NAME - UNKNOWN**

  Main Route – Addis-Galafi

  **District Name - ** Dire Dawa

  Road Segment - Adaitu-Mille

  Bridge Type – RC Deck Girder

  Bridge Length – 62.25m

  Total Damage – 60.59%

  Current condition - The bridge deck slab and girders are cracked. There is void on the deck slab and rebar exposure on the top of the deck slab.

Figure 3.24 Crack and rebar exposure

- **BRIDGE NAME - <u>GUDLESI</u>**

  Main Route – Addis-Galafi

  District Name - Dire Dawa

  Road Segment - Awash-Gedamaitu

  Bridge Type – RC Deck Girder

  Bridge Length – 12.50m

  Total Damage – 28.86%

  Current condition - Severe cracking on the slab and girder ; water leakage on the slab and abutment walls.

Figure 3.25 Crack and water leakage

- **BRIDGE NAME - <u>GEREB-GORMODO</u>**

  Main Route – Addis-Axum

  **District Name - ** Adigrat

  Road Segment - Negasg-Adigrat

  Bridge Type – RC Deck Girder

  Bridge Length – 12.00m

  Total Damage – 12.81%

  Current condition - Cover concrete peel off & water leakage and rebar exposure

Figure 3.26 Water leakage, rebar exposure and spalling of cover concrete

- **BRIDGE NAME - BAHRIYAWITO**

  Main Route – Addis-Axum

  District Name - Adigrat

  Road Segment - Negasg-Adigrat

  Bridge Type – RC Deck Girder

  Bridge Length – 26.00m

  Total Damage – 14.22%

  Current condition - Crack on the abutment, pier and girder, rebar exposure, cover concrete peel off and water leakage on the deck and pier

Figure 3.27 Crack, Water leakage, rebar exposure and spalling of cover concrete

- **BRIDGE NAME -<u>MEHTSAB ALABU</u>**

  Main Route – Addis-Axum

  District Name - Adigrat

  Road Segment - Adigrat-Bizet

  Bridge Type – RC Deck Girder

  Bridge Length – 21.20m

  Total Damage – 11.31%

  Current condition - Crack on the deck slab, rebar exposure & peel of concrete cover on the girder

Figure 3.28 Crack, Water leakage, rebar exposure and spalling of cover concrete

- **BRIDGE NAME -UNKNOWN**

Main Route – Addis-Axum

District Name - Adigrat

Road Segment - Adigrat-Bizet

Bridge Type – RC Deck Girder

Bridge Length – 5.00m

Total Damage – 13.94%

Current condition - Honey comb on the deck slab, rebar exposure & cover concrete peel off on the girder

Figure 3.29 Honey comb on the deck slab, rebar exposure & cover concrete peel off on the girder

- **BRIDGE NAME -UNKNOWN**

  Main Route – Addis-Axum

  District Name - Adigrat

  Road Segment - Adigrat-Bizet

  Bridge Type – RC Deck Girder

  Bridge Length – 5.20m

  Total Damage – 14.70%

  Current condition - Cover concrete peel off and rebar exposure on deck slab

Figure 3.30 Cover concrete peel off and rebar exposure on deck slab

- **BRIDGE NAME -<u>WERWER</u>**

  Main Route – Addis-Axum

  District Name - Adigrat

  Road Segment - Bizet - Adiabun

  Bridge Type – RC Deck Girder

  Bridge Length – 14.90m

  Total Damage – 15.08%

  Current condition - Cover concrete peel off on deck ; rebar exposed and water leakage

Figure 3.31 Cover concrete peel off and rebar exposure on deck slab

- **BRIDGE NAME -UNKNOWN**

  Main Route – Addis-Axum

  **District Name - ** Adigrat

  Road Segment - Bizet **-** Adiabun

  Bridge Type – RC Deck Girder

  Bridge Length – 5.00m

  Total Damage – 12.81%

  Current condition - Water leakage and rebar exposure

Figure 3.32 Water leakages and rebar exposure

- **BRIDGE NAME -<u>BURKA</u>**

  Main Route – Addis-Axum

  District Name - Adigrat

  Road Segment - Bizet - Moheny-Hewane

  Bridge Type – RC Deck Girder

  Bridge Length – 20.00m

  Total Damage – 13.44%

  Current condition - Cracking and Peel of deck slab;honey comb and rebar exposure

Figure 3.33 Cracking and Peel of deck slab, honey comb and rebar exposure

- **BRIDGE NAME -<u>KUMITE 1</u>**

  Main Route – Addis-Axum

  District Name - Alemgena

  Road Segment - Bizet - Aleltu – Sembo

  Bridge Type – RC Slab Culvert

  Bridge Length – 8.60m

  Total Damage – 32.84%

  Current condition - Severe peel off, rebar exposure and voids on the deck slab;honey comb on the deck slab

Figure 3.34 Severe peel off, rebar exposure and voids on the deck slab, honey comb on the deck slab

- **BRIDGE NAME -<u>TEMCHA</u>**

  Main Route – Addis-Gonder

  District Name - Debre Markos

  Road Segment - Dber Markos-Denbecha

  Bridge Type – RC Deck Girder

  Bridge Length – 39.00m

  Total Damage – 11.00%

  Current condition - Water leakage on girder and abutment

Figure 3.35 Water leakage on girder and abutment

- **BRIDGE NAME - <u>JEMIN</u>**

  Main Route – Addis-Gonder

  District Name - Debre Markos

  Road Segment - Denbecha-Bure

  Bridge Type – RC Deck Girder

  Bridge Length – 14.90m

  Total Damage – 23.37%

  Current condition - Honey comb on girder & deck slab; Cover concrete peel off ; rebar exposure and water leakage on the deck slab

Figure 3.36 Honey comb on girder & deck slab; Cover concrete peel off; rebar exposure and water leakage on the deck slab

- **BRIDGE NAME -<u>BERODO</u>**

Main Route – Addis-Gimbi

**District Name - ** Alemgena

Road Segment - Ambo – Gedo

Bridge Type – RC Deck Girder

Bridge Length – 10.00m

Total Damage – 46.28%

Current condition - Severe rebar exposure & honey comb

Figure 3.37 Severe bars exposure & honey comb

4. CORROSION PROTECTION

4.1. GENERAL DESIGN PROVISIONS

It is generally the design details that influence the overall performance and durability of bridge decks and other bridge components, both conventionally reinforced concrete. Some design factors that affect the durability of concrete structures include in the selection and design provisions of the following items,[2]:

- Construction type
- Expansion joints
- Construction joints
- Tendency of concrete to crack
- Duct and anchorage layout in post tensioned concrete.
- Drainage details
- Access for inspection and maintenance
- Proximity to sea water
- Exposure to dicing chemicals

Expansion joints: **-** The effectiveness and lifespan of expansion joints depend on how well they are installed. Whenever possible, construct continuous structures and integral abutments to eliminate expansion joints. However, when joints are used, provide adequate and proper drainage facilities so that water does not reach the anchorages or bearings and does not pond. Include access provisions for the inspection of the joints and structural components under the joint. Even well- constructed joints leak. Whenever possible, locate deck construction joints away from critical areas.

Cracks: **-** Cracks may be thermal or shrinkage. Cracking may also be due to creep or due to the high modulus of elasticity of the hardened concrete. Exercise proper care in the layout and sequencing of concrete pours to minimize the risk of cracking. For post-tensioned structures, provide an adequate amount and distribution of reinforcement in the anchorage areas.

In post-tensioned concrete structures, the ease of grouting will influence the quality of the completed grouting operation. Both tendon profiles and duct size affect the ease of grouting. The location of anchorages affects the ease of stressing and inspection, as well as susceptibility to the ingress of water. Anchorages located in the top surfaces of decks are easy to construct, stress, and grout. However, due to their location, it is easier for crack control, the use of rigid overlays and provisions for good roadway drainage.

Concrete cover: - The use of well-consolidated, lower-permeability adequate concrete cover is a cost-effective corrosion control measure. The amount of concrete cover significantly influences the time-to-corrosion of the steel reinforcing bars and its quality influences the diffusion rate of chloride ions through the concrete. Since the diffusion of chloride ions in concrete is non-linear with increasing cover thickness, there is a significant increase in the time required for the chloride ions to reach the steel reinforcing bars.

However, with increased concrete cover, there is an increase in the potential for concrete cracking from shrinkage and thermal effects. The reinforcing steel bars become less effective for crack control with increasing cover thickness.

Width of cracks: - The width of cracks in concrete is more of a concern than the number of cracks. The use of an increased number of well-distributed reinforcing steel bars is more effective in controlling crack widths than a smaller number of larger bars. The AASHTO standard specifications for highway bridges and the AASHTO load and resistance factor design specifications both require reinforcement for shrinkage and temperature stresses.

There are some precautions that can be taken during the design of a structure to help minimize the potential for corrosion. The number of deck joints should be as few as possible and unnecessary joints should be eliminated. Open joints should be located as far as is practical from critical structural components. Place bearing devices on pedestals and use sloped surfaces on the tops of pier caps and abutment seats to reduce the ponding of salt-contaminated water and minimize the potential deterioration of these bridge elements. Gaps in railing also allow water and chlorides to reach beams. The coupling of dissimilar metals should be avoided to minimize galvanic corrosion.

With careful attention to details, proper deck slopes and the size and spacing of deck drains, adequate deck drainage can be provided. This ensures that water will drain and not pond on the deck. Ponding prolongs the exposure to salt-contaminated water and allows water and chlorides more time to penetrate into the concrete. The use of fewer larger deck drains is generally more effective than smaller drains. In addition, larger drains are not as apt to clog. Drains should be long enough and located so that salt-contaminated water is not discharged onto beams, pier columns and abutments.

In adequate drainage systems and leaky expansion joints allow water and chlorides to reach beam ends as well as piers and abutments. Expansion joints and drainage systems need to be properly maintained. Some common joint defects are deterioration of the joint sealer, lack of a joint sealer and cracking of the concrete around the joints. No joint is perfect and traffic and environmental forces eventually result in joint deterioration and leakage. An adequate joint maintenance program should either replace or repair deteriorated joints.

4.2. GENERAL CONSTRUCTION PROVISIONS

There are several construction variables that influence the durability of concrete structures. These include: [2]

- concrete placing
- consolidating and curing
- rebar placement
- duct and tendon placement
- Grouting procedure and materials

Poor construction practices can also easily negate the best design provisions taken to produce a durable concrete structure.

Good consolidation practices help to avoid segregation and honey combing, while yielding a uniform concrete with low permeability. A well- consolidated concrete can be achieved through the use of proper construction techniques and equipment. Poor consolidation results in concrete with higher permeability and voids, cavities, and poor bonding. Voids, cavities and areas of poor bonding aid in the corrosion process. Poor procedure for grouting post-tensioning ducts can leave voids where moisture can accumulate and initiate corrosion of the pre-stressing tendons. In post-tensioned structures, certain grouts can cause severe corrosion if the excess mix water bleeds into the voided areas and is not absorbed into the grout during hardening

The proper and through consolidation of the concrete ensures that concrete is in intimate contact with the steel reinforcing bars. A good bond between the steel reinforcing bars and the surrounding concrete is critical for corrosion control. As a result of the intimate contact between the steel reinforcing bars and the concrete, the steel will be in the high-alkaline environment, necessary for the formation and maintenance of the passive oxide film. Exercise extra care when placing and consolidating concrete around embedded or partially embedded items so that water and chlorides do not have easy access to the steel reinforcing bars. When using epoxy-coated reinforcing steel, concrete consolidation should be done with a vibrator having a rubber-coated head.

The curing procedures are an important part of workmanship. Proper and adequate curing provides durable concrete through increased cement hydration. A minimum of 7 days of uninterrupted moist cure is recommended. Whatever the curing method used, the surface of the concrete must be kept wet. Alternating wet-dry cycles promotes cracking the concrete. There are three general categories of curing methods. A continuous water cure is done by a continuous spray, ponded water, or saturated surface coverings. Curing compounds seal the surface of the concrete. Moisture barrier materials, such as plastic sheets or waterproof paper, cover the surface of the concrete. Continuous water cure supplies sufficient water to prevent the surface of the concrete from drying. Both membranes and moisture barriers work by preventing evaporation of the mix water from the surface of the concrete.

The accurate placement of steel reinforcing bars ensures that an adequate concrete cover over the bars will be obtained. Methods for placing and tying bars to ensure proper cover include the use of chairs, spacers and form ties. Allowances for tolerances in bending bars may also be needed. Reinforcing steel should be adequately tied to prevent it from moving from the desired location during concrete placement and consolidation. Reinforcement support and ties should have adequate strength to carry construction loading before and during concrete placement and to avoid excessive deflection of the reinforcing steel.

4.3. SELECTION OF PROTECTION SYSTEMS

It is always preferable to use protection systems. When selection of protection system is done, it should be noted that the protection system chosen must be cost effective, long lasting and easier to maintain, easier to use and environment friendly. Moreover, each corrosion protection system must be selected based on the expected exposure of the structure to corrosive elements over its lifetime.

Based on these facts, the following protection systems can be used, [4]:

- Keep concrete always dry, so that there is no water to form rust. Also aggressive agents cannot easily diffuse into dry concrete. If concrete is always wet, then there will not be oxygen to form rust.
- FLY ASH: Using a Fly Ash concrete with very low permeability, which will delay the arrival of carbonation and chlorides at the level of the steel reinforcement. Fly Ash is a finely divided silica rich powder that, in itself, gives no benefit when added to a concrete mixture, unless it can react with the calcium hydroxide formed in the first few days of hydration. Together they form a calcium silica hydrate (CSH) compound that over time effectively reduces concrete diffusivity to oxygen, carbon dioxide, water and chloride ions.
- A portion of the chloride ions diffusing through the concrete can be sequestered in the concrete by combining them with the tri-calcium aluminate to form a calcium chloro-aluminate (Friedel's salt). It can have a significant effect in reducing the amount of available chlorides thereby reducing corrosion.
- Electrochemical injection of the organic base corrosion inhibitors, ethanolamine and guanidine, into carbonated concrete.

- The rougher the steel surface, the better it adheres to concrete. Oxidation treatment (by water immersion and ozone exposure) of rebar increases the bond strength between steel and cement paste to a value higher than that attained by clean reinforcements. In addition, surface deformations on the rebar (such as ribs) enhance the bond due to mechanical interlocking between rebar and concrete.
- As the cement content of the concrete increases (for a fixed amount of chloride in the concrete), more chloride reacts to form solid phases, so reducing the amount in solution (and the risk of corrosion), and as the physical properties improve, the extent of carbonation declines, so preventing further liberation of chloride from the solid phase.
- Electrochemical Chloride Extraction (ECE) is a relatively new technology for which long-term service data are limited. This method employs a temporary anode that is operated at current density orders of magnitude higher than for cathodic protection, such that anions, including chlorides, electro migrate away from the embedded steel cathode. Repassivation can then occur, similar to what was discussed above in conjunction with cathodic protection, although this occurs in a shorter period of time (1–2 weeks to several months). Not all chlorides are removed, but sufficient amounts are displaced from the steel-concrete interface.
- Installation of physical barrier systems such as coatings, sealers, membranes, and overlays to forestall subsequent Cl- ingress
- A relatively thin zinc surface layer is applied by either hot dipping or electro-deposition. This methodology relies on a relatively low corrosion rate for zinc and its potential for being active to the substrate steel, thereby providing galvanic cathodic protection at defects and penetrations.
- Cathodic prevention is, in effect, identical to cathodic protection, except that it is applied to new, Cl-free structures for which current demand is less than for Cl contaminated ones. In addition, the objective here is not to reduce corrosion rate itself (because the reinforcement is passive), but instead to establish a potential gradient that opposes the inward diffusion migration of anions, specifically chlorides. In this regard, the approach functions similarly to ECE, except that, instead of removing chlorides, it retards their entry.
- Concrete mix design modifications involve such factors as reduced w/c, including use of water reducing admixtures or super plasticizers; type of cement; permeability reducing admixtures such as fly ash, silica fume, and blast furnace slag; and corrosion inhibiting admixtures.
- Structural design aspects of corrosion control involve factors such as configurational (geometrical) considerations that minimize or, if possible, eliminate exposure to corrosives.

- Remedies for corrosion-damaged concrete include removal of all delaminated concrete, cleaning of the reinforcement by abrasive blast cleaning, high pressure water, or needle scaling, and use of a concrete patching material.

4.4. DEVELOP AWARENESS ON THE PROBLEM

The subject of corrosion has undergone an irreversible transformation from a state of isolated and obscurity to a recognized discipline of engineering. From the three universities in USA which offered courses in corrosion in 1946, corrosion courses are now offered by almost all major technical universities and institutions in USA, UK, Europe, South-East Asia, Africa and Japan. Corrosion is now considered as an essential component of design. Learned societies like National Association of Corrosion Engineers, European Federation of Corrosion, Japan Society of Corrosion Engineers and others are playing leading role in the development of corrosion engineering education, [11].

Detailed information on corrosion education, training centers, opportunities in corrosion can be found in various handbooks and websites. As a consequence of cumulative efforts of corrosion scientists and engineers, corrosion engineering has made quantum leaps and it is actively contributing to technological advancement ranging from building structures to aerospace vehicles, [11].

When we come to our country experience, much has to be done in the area of the field. A lot must be learned from the developed countries and is better to develop awareness to students. Corrosion engineering must be offered as a course at the university level so that awareness will be given during design and construction. Consequently, a lot of money can be saved and also attention will be given to the poor workmanship and methods of construction.

5. CORROSION CONTROL MEASURES

5.1. CORROSION INHIBITORS

Corrosion inhibitors, [2], are chemical admixtures added to Portland cement concrete mixes during batching usually in very small concentrations – as a corrosion protection measure. Corrosion inhibitors are a viable corrosion-protection measure for the long-term durability of both conventionally reinforced and pre-stressed concrete bridge structures. When used as part of multiple-strategy corrosion –protection system, they are promising materials to delay the onset of reinforcing and pre-stressing steel corrosion.

Inhibitors are often used in combination with low-permeability concrete and usually they have the effect of increasing the threshold chloride concentration needed to initiate corrosion. Inhibitors play an important role in protecting uncoated high-strength steel strands used in pre-stressed concrete bridge members and stays used in cable-stayed bridges. They are also used in cementitious grouts for filling the ducts of bonded post-tensioned bridges. Inhibitors may also reduce the subsequent corrosion rate after the initiation of corrosion, which ultimately leads to less corrosion-induced concrete deterioration.

There are three major concerns regarding the use of corrosion inhibitors.

- Long-term stability and performance of the inhibitor.
- Inhibitor's effect on corrosion propagation after corrosion initiation.
- Inhibitor's effect on the concrete's physical properties over the service life of the structures.

In order for a corrosion inhibitor to be an effective long-term corrosion protection measure, it needs to be able to maintain long-term stability. It should be chemically intact and physically present (not leaching or evaporating) to retain its effectiveness.

Inhibitors may have an effect on the corrosion process after corrosion initiation. An insufficient dosage will have a negative impact on corrosion progression. Some inhibitors will have an effect on chloride transport and can reduce the rate of chloride ion migration.

Inhibitors should not have any negative effects on the concrete properties. The use of an inhibitor should not cause an undue increase in the amount of any concrete cracking. Some inhibitors decrease the concrete resistivity, which has a tendency to increase the corrosion rate. This effect is offset due to the inhibition provided by a suitable corrosion inhibitor.

Corrosion inhibitors are either inorganic or organic and, in general, are classified based on their protection mechanism. They can protect by affecting the anodic reaction, the cathodic reaction, or both reactions (mixed). An active type of inhibitor (anodic) facilitates the formation of an oxide film on the surface of the steel reinforcing bars. Passive systems protect by reducing the rate of chloride ion migration. Calcium nitrite is an inorganic inhibitor. It protects the steel reinforcing bars through oxidation-reduction reactions at the steel surface. Organic inhibitors consist primarily of amines and esters. They form a protective film on the surface of steel reinforcing bars and sometimes delay the arrival of chloride ions at the steel reinforcing bars.

There are four major commercially available corrosion inhibitors:

- **DCI-S (DAREX CORROSION INHIBITOR)**–is a corrosion inhibitor added to the concrete during the batching process and inhibits the corrosive action of chlorides on reinforcing steel and this inturn extends the service life of structures. It is cost effective and easy to use.
- **RHEOCRETE 222^{+}-** is formulated to inhibit the corrosion of steel in concrete by forming a durable and strong protective film on the reinforcing steel and this film dramatically slows the corrosion process by preventing chlorides from reacting with the reinforcing steel, therefore, slowing the rate of corrosion once it begins.
- **MCI 2000 (MIGRATORY CORROSION INHIBITOR)-** is a liquid concrete admixture when added to the concrete mix, seeks out and forms a corrosion inhibiting layer on the metals. When used with repair mortars and grouts, it will migrate to adjacent areas to protect the surrounding re-bars. It does not affect the physical properties of the concrete mix. It is organic, safe and environmentally friendly.
- **FERROGARD 901** – penetrates through concrete to the steel reinforcement, where it is adsorbed onto the surface and forms a continuous protective film around the steel presenting a physical barrier to chlorides and other deleterious substances. It also displaces chloride ions from the metal surface to protect concrete form the steel surface.

5.2. CORROSION RESISTANT REINFORCING BARS (EPOXY–COATED)

The primary cause of the deterioration of reinforced concrete structures is the corrosion of steel reinforcing bars due to chlorides. Epoxy-coated reinforcing steel (ECR) was developed and implemented in the mid- 1970's to minimize concrete deterioration caused by corrosion of the reinforcing steel and to extend the useful life of highway structures. The epoxy coating is a barrier system intended to prevent moisture and chlorides from reaching the surface of the reinforcing steel and to electrically insulate the steel to minimize the flow of corrosion current, [2].

Epoxy coating consists of organic epoxy resins united with curing agents because it is intended to provide a physical barrier between chlorides and oxygen absorbed in the concrete and the reinforcing steel. Once it is cured, epoxy coating is a thermo-set material; it is not subject to damage by high temperatures.

In order to provide an uneven surface for the epoxy to bond mechanically as well as chemically, the surface of the steel must be cleaned and roughened with abrasive material. It is then heated and passed through a sprayer which charges the epoxy powder and causes it to evenly coat the surface of the steel. The heated steel melts the powder that is sprayed on the steel. Then, it initiates the chemical reaction that forms complex polymers in the epoxy and bonds the epoxy molecules to each other and the rough steel surface.

Furthermore, the epoxy coating also has a high electrical resistance and avoids the flow of electrons that facilitate electrochemical corrosion. The necessary mechanical properties for use in coating such as ductility and negligible shrinkage after application are possessed by epoxy coating. It is also durable to rough handling and weathering, flexible, environmentally friendly and very efficient method of manufacture and application to the steel as well.

Epoxy-coated reinforcement is generally required in roadways and bridge decks where deicing salts cause significant chloride contamination to the concrete. The ACT code lists ASTM standards A775 and A934 as the accepted specifications for epoxy coated steel reinforcing bars, [1].

ECR was first used to reinforce a four-span bridge deck over Pennsylvania's Schuylkill River in 1973. By 1975 ten states had implemented ECR in bridge deck construction, and within a decade nearly all states with freeze-thaw cycle climates or salty coasts had adopted the material. The Canadian Ministry of Transportation of Ontario standardized the use of ECR in bridge decks in 1978, and for bridge substructure components in 1981. Today EC is the most widely used rebar corrosion protection method for bridge deck reinforcement, [1].

Further research is required on the durability of ECR in this application.

Drawbacks of ECR

A disadvantage of substituting epoxy-coated reinforcement in place of uncoated steel is that:

- It has poor chemical adhesion to the cement mortar mix, resulting in lower bond strength between the rebar and concrete.
- It reduces the size of the rebar deformation ribs and provides less friction to resist bond slip
- The reduction in bond strength is a product of the rebar size, with larger bar diameters resulting in lower relative bond strength.
- Bond slip creates cracking in the concrete, and epoxy coated bars were found to create fewer but wider cracks in concrete as a result of bond slip.
- The bond between the epoxy coating and the steel rebar also tends to deteriorate over time and exposure to moisture.

Figure 5.1 Bridge deck concrete placements (epoxy coated reinforcement bars)

5.3. CATHODIC PROTECTION

Corrosion of the reinforcing steel in concrete has gained much attention in recent years because of the decaying infrastructure of highways and bridges. States, federal agencies and other researchers indicate that cathodic protection is a proven method for corrosion control of concrete reinforcing, [7].

Concrete structures normally rely on the concrete cover to provide protection that prevents the corrosion of embedded steel. Over time, this protection can be lost due to moisture and/or chloride ingress. When the corrosion of the embedded steel occurs, cathodic protection can be used to extend the life of the already deteriorated structure, [7].

Cathodic protection systems (CP) [9] have an excellent track record in corrosioncontrol of steel and reinforced concrete structures. The principleof CP is that the electrical potential of the steel reinforcement is artificiallydecreased by providing an additional anode system at the concretesurface. An external current is required between anode and cathode thatdiminishes the corrosion rate along embedded reinforcement. The currentmay be produced either by a sacrificial anode system or using animpressed current from an external power source.

Sacrificial anode systems consist of metals higher than steel in the electrochemical series (e.g. zinc). The external anode corrodes preferentially to the steel and supplies electrons to the cathodic steel surface. Sacrificial anode systems are most effective in submerged structures where the concrete is wet and resistivity is low. Warm temperatures are also generally required for sacrificial CP systems (i.e. above 20^0C).CP systems more commonly use an external electrical power source to supply electrons from anode to cathode. The anode is placed near the surface and is connected to the reinforcement through a transformer rectifier that supplies the impressed current (see Figure 5.3). Anodes may be conductive overlays, titanium mesh within a sprayed concrete overlay, discrete anodes or conductive paint systems. Anode systems are usuallydesigned for a minimum service life of 20 years but may last in excess of50 years.

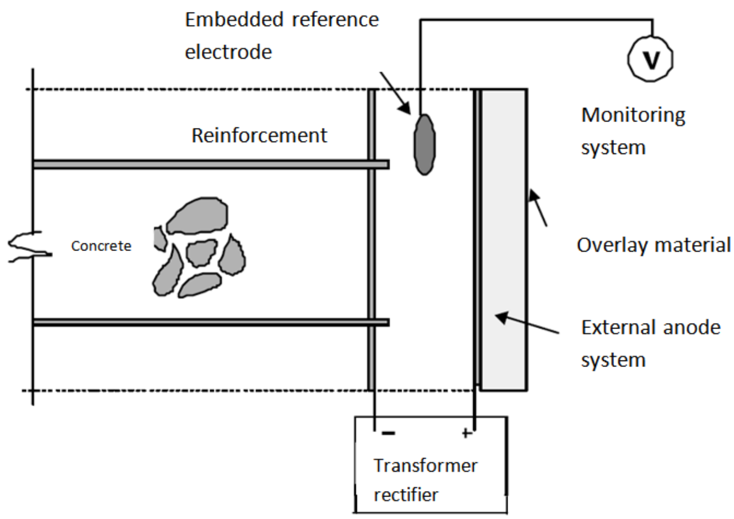

Figure5.2 Typical cathodic protection layout

CP repair of concrete structures requires a thorough corrosion survey by a specialist and the design needs to be undertaken by a corrosion expert. Reliable CP systems are fully controlled and monitored by a series of embedded sensors in order to ensure optimum performance. This is essential since under or over-protection of the reinforcement may be potentially harmful to the structure or the CP system. Continuous monitoring of CP systems is usually done remotely by modem and the power consumption during operation is extremely small.

5.4. DEMOLITION/RECONSTRUCTION

Deterioration of reinforced [9] concrete structures is often so advanced that demolition and reconstruction becomes viable. This option should only be considered as a last resort since the total cost (capital costs plus loss of service and temporary works) is usually well in excess of repairs costs. Corrosion damage is also generally confined to near-surface regions and engineers often over-estimate the extent of damage to corrosion-damaged structures.

Demolition and reconstruction is often preferred by engineers whohave limited repair experience or lack confidence in new repair systems.It is crucial nevertheless those lessons are learnt from the old structure when designing the replacement.

6. REPAIR OF CORROSION AFFECTED REINFORCED CONCRETE STRUCTURES

6.1. REPAIR OF A SEVERELY CORROSION DAMAGED MEMBER

The following procedure can be applied for repair of a severely corrosion damaged member, where cover concrete has spallen and reinforcement (reduced in cross-sectional area) has been exposed:

Step 1: The repair process is started by cutting away all the loose and deteriorated concrete until the hard core is reached preferably behind the corroding reinforcement.

Step 2: All exposed reinforcements must be thoroughly cleaned. Loose rust or any contamination is removed by abrasive blast cleaning. (Note that, wire brushing by hand is not usually effective.)

Step 3: The portions of steel bars severely corroded require replacement. This is achieved by cutting away the corroded portions and replacing with new bars of the same type and size, either welded or tied to the existing bars.

Step 4: After the corrosion affected bars are replaced in position, immediately a protective primer (Zinc, neat resin or any other suitable coating) is applied. The primer chosen should be such that it should have good adhesive strength and good adhesion to subsequent repair layers.

Step 5: In order to build up the section, either cement based repair, or Resin based repair can be carried out as discussed below.

6.2. STRUCTURAL REPAIR BASED ON EXTENT OF DAMAGE

6.2.1.CEMENT BASED REPAIRS:

i) The slurry (bonding coat) is applied to all concrete surfaces to which bond is required and the patching mortar (readily available in pre-weighed packets) is applied, while the slurry is still tacky. (Care should be taken to wet the concrete surface before the application of the material but there must be no standing water left on the surfaces).

ii) After the prepared surfaces have been coated with bonding agent or a coating of neat cement slurry, the repair material consisting of 1:3(cement and sand) is applied in layers not exceeding 20mm thick. Each layer is to be keyed to receive the succeeding layers. The outer layers of cement should not be thicker than the inner layers. This is required, in order to prevent failure due to shrinkage stresses.

It should be ensured that the cement-based materials used in repairs do not dry out quickly. The method ofcuring depends on the local conditions. Water soaked covers and curing membranes are common ways of protection.

6.2.2.RESIN BASED REPAIRS

The priming coat is applied over the prepared surfaces to protect the surfaces. The interval between coats should not be too long; otherwise there will be bond failure.

Resin-based materials cure by exothermic chemical reaction immediately, when the constituents are mixed. It is essential that the materials should be well compacted to become impermeable, because they do not protect the steel by alkalinity.

6.2.3.LARGE VOLUME REPAIR

When a large volume of repair material is to be placed in members that have been extensively damaged, it becomes necessary to fix some kind of formwork and fill it with concrete or grout. The concrete is usually placed in conventional ways (poured concrete) or it may be formed by injecting grout into a mass of dry aggregate (under water work concrete).

6.2.4.POURED CONCRETE

Defective concrete is first removed and loose concrete is chipped away from the face and around the reinforcement. Additional reinforcement can be provided by securely fastening it to the existing bars. It is necessary to protect thereinforcement by applying coating in the form of corrosion inhibiting paint likecement based polymer slurry or a resin based slurry. The formwork is so designed that the concrete fills it completely without leaving any air pockets. The joints in the formwork are sealed completely to avoid any leakage. Depending on the thickness to be poured, aggregate of maximum 20mm size (for thickness greater than 100mm) is adopted in the concrete mix, with suitable shrinkage compensating agent. In order to ensure good compaction of concrete, material vibration or external vibration using a mechanical hammer on the formwork can be imparted.

6.2.5.REPLACED CONCRETE

The technique is best suited for certain types of repair, particularly in under water work. In this method, the formwork is erected in the normal way but it is first filled with clean specified (depending on thickness) coarse aggregate. Later cement grout is pumped into the forms from bottom until all the voids are filled as the air or water is vented at the top. It is essential that the formwork is watertight and is designed to withstand the full hydrostatic head of grout. This method offers quality concrete without segregation with minimum during shrinkage. This disadvantage is that the injected cement paste is prone to bleeding.

6.2.6.SEALING OF CRACKS

Sealing of cracks by repair materials will be effective only when proper materials are injected. For this, the cause of crack has to be determined. If the cause of the crack is such that it is unlikely to recur, then it can be filled with a rigid material. But, if the crack is caused due to movement and that is likely to continue then any attempt to seal the crack against further movement may cause a new crack along the side of the old one.

6.2.7.REPAIR OF CRACKS (WHERE FURTHER MOVEMENT IS EXPECTED)

Such cracks can be sealed to prevent moisture penetration by simply brushing latex emulsion of low viscosity or cement paste containing fine quartz powder filler. The procedure for carrying out this type of repair is as follows:

Step 1: The crack is thoroughly cleaned using compressed air.

Step 2: Superficial seal is applied over the crack at the surface by using a fast setting polyester resin or a thermoplastic material into which injection nipples are fixed at intervals.

Step 3:Injection is started at the lowest point and when resin reaches the next higher point, the injection gun is moved up to the next and the lower point is sealed. The process is continued until the whole crack gets sealed. The pressure used is carefully controlled to avoid bursting of the seal and concrete scale work.

6.2.8.REPAIR OF CRACKS (WHERE FURTHER MOVEMENT IS EXPECTED)

When a crack is subjected to continuing movement, it is absolutely necessary to reduce the strain in it to reasonable amount. This can be easily done by widening the crack at the surface and sealing it with an elastic material such as polysulphide rubber or a performed neoprene strip.

6.2.9. SURFACE COATINGS

It is necessary that after the completion of repair work, to treat both the repaired areas and the rest of the structure with some coatings, principally, to reduce the permeability of concrete, to moisture, carbon dioxide, and other aggressive agents. The coatings further can also give aesthetic look to the structure by containing the patches, discolouration and stains and match colour and textures.

Several coatings are available in the market, which can be readily used on the repaired surfaces as per the instructions of the manufacturer.

6.2.10. DRY PACKING

Dry packing or plugging is the hand placement of a low w/c ratio mortar followed by ramming or tamping of mortar into place producing an intimate contact between new and existing work. The method is applicable to dormant cracks in a structure. Shrinkage is considerably reduced. It provides good strength and water tightness increasing the durability. Care is to be taken to use well-graded sand in the mortar mix.

7. CONCLUSION

This thesis provides a comprehensive description of issues and solutions involved in reinforcing concrete structures with steel rebar.

The economic loss caused by corrosion damage of reinforced concrete structures and risks associated with the corrosion of steel in concrete have been recognised in developed countries. But much has to be done in Ethiopian practice since professionals and practitioners in the construction industry are not aware of corrosion effects and damages.

As it is attempted to illustrate corrosion in built structures, many structures in our country are suffering from corrosion and factors related to corrosion such as cracks, leakage, moisture, spalling of cover concrete, rebar exposure and others. Therefore, it is evidence that corrosion is a risk to our country civil engineering structures.

In our country practice, it is advantageous to know the extent of corrosion in reinforced concrete structures using resistivity meter and corrosion analyzing instrument. As a result, the available corrosion control measures can be used at an early stage. In addition, it is desirable to monitor the condition of structures right from the construction stage by carrying out periodic corrosion surveys and maintaining a record of data. Furthermore, the design should also be done with great care.

Inaccessible details that do not allow for inspection and maintenance are poor design practices and must be avoided. Moreover, concrete placing, curing, rebar placement, grouting procedures and materials should be properly done. The poor reinforcement bar storage, handling and installation trends should be avoided and the inadequate quality control and negligence which in turn cause poor construction methods and workmanship should be improved. Since there are many repair options available; cost, technical feasibility and reliability must be considered. Professionals need to understand all the relevant material, structural and environmental issues associated with concrete repairs in order to make intelligent choices.

In our country, many civil engineering structures are constructed and under construction. A lot of money is being spent on those projects and others. Hence, it is better to think about the damages that result due to negligence and unawareness at early stages. It is going to be very disappointing if the structures fail and lose the lives of many while a lot can be done from the design stage to the final stage of construction. Therefore, properly monitoring the structures for corrosion performance and taking suitable measures at the appropriate time could help enormous saving in life and also cost aspect.

As long as metallic materials are used in concrete, and as long as the concrete is not free of defects, corrosion problems will not be avoided. Consequently, much attention must be given in developing awareness on the problem. Detailed information on corrosion education must be given in higher education institutes and some short term trainings in construction site to all workers.Otherwise, it is going to cause a great damage to the whole country economic system.

7.1. RECOMMENDATION

Future study may be made on the following:

- Assessment study on life of corrosion caused failure structures in Ethiopia.
- For most structures, laboratory and field tests must be conducted to determine corrosion rate in service life estimation.
- Cost comparison should be made for the available corrosion control measures putting into account our environmental condition, workmanship, maintenance techniques and expected exposure of the structure to corrosive elements over its lifetime.
- The use of admixtures and sealers can be evaluated to different bridge decks. Testing of sealers and admixtures in the field can be expanded. In addition, a long-term study on the use of admixtures and sealers should be implemented.
- Calculations and estimates can be done to determine construction and repair costs for bridge decks and times to repair and/or replacement.

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