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Durability of Concrete and Reinforcement Corrosion in Concrete Bridge
Decks and Parking Structures

By

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A Project and case study submitted in partial fulfillment of the
requirements

for the degree of Master of Engineering

Department of Civil Engineering

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ABSTRACT

The deterioration of concrete can be due to: (1) the corrosion of reinforcement; (2) freezing and thawing, including frost damage; (3) chloride ingress; (4) carbonation of concrete; (5) sulphate attack; (6) acid attack; (7) alkali attack; (8) alkali – aggregate reaction; (9) salt attack; and (10) abrasion. Investigation of the durability of concrete generally consists of either the causes of deterioration or the extent of it. Usually, methods used to improve the durability of concrete aim to prevent the causes of deterioration; however, occasionally methods that limit the extent of damage are employed. In this context, and in order to propose test, which can assess the durability between the material properties and deterioration mechanisms, is carried out. Such an analysis should help to focus the attention of various investigators the key issues that ultimately determine the durability of concrete structures.

Concerning the various deterioration mechanisms described above, one of the fundamental properties that influences the initiation and extent of damage of concrete is corrosion of reinforcement in the concrete structure. Environmental effects such as the freezing and thawing cycles have caused deterioration of the bridge decks and all other exposed reinforced concrete structures. Concrete is full of microcracks even when it is not loaded. When under vehicular traffic, some structural cracks form that can join the other already existing cracks, providing an easy route to reinforcing steel for the deicing salt. The presence of shrinkage and temperature cracks can also do the same. When chloride ions along with moisture reach the level of reinforcing steel, they start corroding the steel reinforcement.

Corrosion of steel reinforcement in concrete bridge decks and parking structures is one of the most common types of deterioration, which has substantially reduced the useful life of such facilities. This widespread problem and the rapidly

increasing cost of maintenance and repair have resulted in great economic and social repercussions. The rising rate of the use of chloride deicing salt is a major factor causing corrosion, and there is no feasible economic alternative to its use at present.

Corrosion may occupy a greater volume than the parent steel reinforcement, thereby extending pressure on the upper concrete, causing it to spall off the main body of concrete. Common types of deterioration and corrosion mechanisms of reinforcement in concrete are reviewed with the view of effects of the concrete environment on the process. It is feasible to study the effect of the individual and combined causes on the onset and rate of reinforcement corrosion.

The role of concrete design and construction practices is discussed as the first protection resort available against corrosion. The importance of concrete quality in providing protection to reinforcement cannot be overemphasized. Bleeding of concrete, which may happen during construction, can result in unfavorable consequences and lead to unfavorable consequences and also to premature corrosion of steel.

The limitations and applicabilities of the various repair techniques and protective measures in existing structures, of course, have differential impacts on concrete in various environments. Cathodic protection is considered the most versatile and effective means of controlling the corrosion of steel and subsequent deterioration of the concrete.

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1. INTRODUCTION

Deicing salts are used increasingly on roads and expressways to melt the snow and ice and to provide traction. The rate of use of deicing salt has been on the increase in the past few years. Many studies have reported that the use of deicing salt is linked to the increasing deterioration of bridge deck and parking structures due to corrosion of reinforcement and other deterioration mechanisms.

The concrete cover usually provides adequate corrosion protection to the steel reinforcement. Most metals form a natural protective film on their surface after being exposed to air for a period of time. In a sense this is corrosion, but once formed it prevents further corrosion as long as the film remains intact. A tightly adhering film that passivates the steel and protects it from corrosion is usually formed as a result of the high alkaline environment in concrete. Furthermore, using a low water/cement ratio together with good quality workmanship leads to low-permeability concrete, which can minimize the ingress of moisture and air that can cause corrosion after the protective barrier is damaged or lost.

Chloride can be bound by the concrete, chemically (by aluminates in the concrete) and physically (by adsorption on the pore walls), the extent of binding and its effectiveness is not well understood. However, it is known that a reduction in pH as caused by carbonation will break down the chloraluminates. This leads to a "wave" of chlorides moving in front of the carbonation front. Consequently, structures with chlorides in them that carbonate are more susceptible to corrosion than those with only one of these compounds [59].

Both chloride and carbon dioxide may penetrate to the steel surface through cracks in some order of magnitude faster than through uncracked concrete. The times

taken for depassivation to occur depends on the crack widths; however, the times involved are negligible compared to the lifetime of reinforced concrete structure.

Corrosion in metals is caused by the flow of electricity from one metal to another or from one part of the surface of a metal to another where conditions permit the flow of electricity. This flow of energy can take place only with a moist conductor; i.e., an electrolyte must be present. Therefore, if corrosion is to take place in a metal there must be an electrolyte, an area or region of the metallic surface with a negative charge in relation to a second area having a positive in opposition to the first area. This flow of energy need not take place within one piece of metal. It may flow between a metal and some kind of metal recipient, such as the soil or concrete, or it could take place between two dissimilar metals. If the soil is electrically negative relative to the metal and an electrolyte such as water or moisture is present, corrosion of metal will result.

There are four substances or materials prerequisite to the electrochemical reactions required for corrosion to take place in a reinforced concrete structure:

An anode: an electrode by which the ions go into solution and electrons are released:

A cathode: an electrode by which the electrons are consumed in the presence of water and oxygen:

A conductor: the steel itself, which permits the transfer of electrons from the anodes to the cathode: and

An electrolyte: moist concrete, which permits the movement of ions between the cathode and anode through the pores containing moisture.

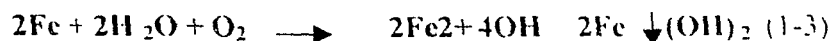
The hydroxyl ions produced due to the cathodic reaction combine with the ferrous ions at the anode to form ferrous hydroxide, and oxidation converts it into insoluble hydrous ferric oxide or rust.



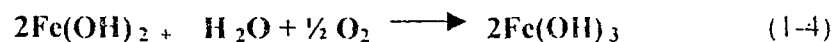
Since the medium is exposed to moisture or water, the cathodic reaction is:



Remembering that sodium and chloride ions do not participate in the reaction, the overall reaction can be obtained by adding the above two reactions.



Ferrous hydroxide precipitates from the solution.



The final product is the familiar rust.

The electrical resistivity of concrete is increased by the low permeability of the concrete, which impedes the electrical current flow. Corrosion of steel occurs in all structures although to a very low and imperceptible level in many structures. However, corrosion of steel can occur if concrete is not of good quality, if the design and construction aspects were not properly coordinated for the service environment, or if the service environment was changed after construction [1].

Corrosion of steel in concrete has received renewed interest in the last three decades because of the rapid deterioration caused in certain types of structures and the increasing cost of repair and maintenance [1]. The consequences of corrosion of embedded reinforcement bars in concrete were experienced earlier in off-shore and coastal structures and in chemical factories. Usually it occurs in bridges, parking garage structures and in some structures that are exposed to an aggressive environment [1].

There are five main sources of trouble in the deterioration of parking structures and bridge decks: the corrosive effects of deicing salts; defective expansion joints; structural movement due to the effects of temperature and humidity; improperly protected hardware (embedded parts, etc.); and attack due to effects of the freezing-thawing cycle.

The effects of deicing salts on reinforcing steel, particularly in the upper portions of unsealed slabs, are a major cause of damage. The salt water enters the decks either rapidly through the cracks or it slowly permeates the sound concrete; chlorides damage the passive protective layer on the steel reinforcement. It is carbonation that lowers pH of the concrete.

The chemically aggressive substances such as carbon dioxide, sulphates, chlorides, oxygen and moisture greatly affect the onset and increase of the level of the corrosion of reinforcing steel. Macrocells start to form on the reinforcing bars once there is a difference in the electropotential as a result of inhomogeneities in the hardened cement paste along the surface of rebars. The electropotential differences can arise from many causes such as the gradient in chloride ion content, freezing-thawing cycles, carbonation of portland cement paste, cracks in the concrete, stray currents, galvanic effects due to local differences in the properties of concrete, or exposure conditions [1]. Construction practices also play an important role in the development and propagation of steel corrosion. One of the most important factors is crack formation in the hardened concrete due to subsidence of concrete during the bleeding process, as will be discussed later. The concrete mixture details and depth of the protective concrete cover particularly affect the capacity and rate of corrosion of reinforcement bars [1].

The transformation of metallic iron into rust results in an increase in the volume and process of the formation of rust, the pressure exerted on the surrounding concrete, the pressure exerted can greatly exceed the ability of even the strongest concrete to resist the resulting tensile stresses. As a result, the concrete cracks, and if the corrosion continues, it can spall off [1]. It is a fact that corrosion causes loss of bond strength between the steel and concrete, but others have pointed out that friction and adhesion between concrete and steel are generally reduced by the absence of a rusty surface [5]. In structures containing high-strength prestressing steel, the reduction in steel cross-section area is of great interest because brittle failure may be induced because of a small amount of steel loss caused by corrosion. A very localized anodic process may lead to cracking due to high permanent stresses, if the steel is sensitive to this type of failure. During the crack propagation stage, the anodic process occurs at the root of the crack. This type of brittle cracking is called stress corrosion cracking (SCC) [5].

The second type of brittle failure is a consequence of the cathodic process. Under certain conditions, atomic hydrogen is developed during the cathodic process as an intermediate product, and it may penetrate into the steel. The recombination to molecular

hydrogen within the steel leads to high local internal pressure and may, consequently, lead to cracking. This type of failure is called hydrogen embrittlement (HE) [5].

The quality of concrete is by far the most important factor in providing protection against corrosion of steel, limiting the intrusion of chloride ions in reinforced concrete. Other preventive measures in use include the application of protective coating on reinforcement in new construction, the use of corrosion inhibitors, and cathodic protection in bridge decks and parking structures [1].

1.1 Scope

Reinforced concrete is a relatively new construction material, developed and applied extensively only in the 20th century. When it first appeared, reinforced concrete was regarded as an artificial stone that neither rusted like steel nor rotted or burned like wood and lasted long. It has always been stated that the combination of concrete and reinforcing steel is an optimal one not only because of mechanical performance but also from the point of view of long-term performance. The earlier decades of plain and reinforced concrete structures, however, revealed complex interaction between reinforced concrete and its environment.

The 20th century became a part of history, leaving a legacy of many accomplishments as well as disappointments. Now is an appropriate time to look into the future and learn from the past. Due to heightened public awareness of energy, resources and ecological issues, and billions of dollars spent every year on bridge and parking structure maintenance and rehabilitation, the problem of infrastructure deterioration needs greater attention and must be tackled with care.

Considerable research has been carried out in the technology sector related to the achievement of durable bridge decks and parking structures and to identify the most suitable solutions, which could be developed further into realistic programs for rehabilitation of existing structures. The problem of corrosion prevention and control is best solved prior to and during the design stage. In order to make basic design decisions,

it is necessary to understand the mechanism of corrosion. Because of the efforts of researchers around the world, new data are continually being made available and may help future construction in the way some aspects of the corrosion problems and their solutions are viewed.

Many factors influence corrosion mechanisms in reinforcing steel embedded in concrete and its rehabilitation; and protection of bridge decks, parking and other structures exposed to aggressive corrosion environments. There is much concern across Canada, United States, the Middle East and around the world regarding the problem of deterioration of such structures, and the causes, prevention, and specific measures that can be taken.

The purpose of this study is to provide a summary of the principles of corrosion, various methods of investigation and rehabilitation of corrosion, assessing deteriorated structures, construction practices, and concrete quality. The projects also discuss a case study of the rehabilitation of 19th Avenue Bridge, in Markham, Ontario. In this bridge the deck and beam soffits of the bridge structure were severely deteriorated due to corrosion of the reinforcing steel, spalling and the lack of proper gradient in bridge decks. The bridge was originally built in 1928 and partly rehabilitated in 1957, when only the deck was replaced.

2 COMMON TYPES OF DETERIORATION

2.1 Common Exposure Conditions

The most serious problem in concrete technology today is the premature deterioration of concrete structures that are subjected to harsh environments. There is overwhelming evidence from field experience that many of the durability problems, such as sulphate attack, reinforcement corrosion, carbonation, and alkali-silica reaction in concrete would not have occurred if the concrete had been made impermeable at the time of exposure to the environment and during the intended service life [4].

The durability-related issue in selecting must be addressed in selecting materials, aggregate mix proportions, and construction practices using concrete. The industry must develop new, comprehensive models of concrete deterioration and the quantification of environmental influences on the permeability of concrete.

Concrete bridge decks and parking structures typically have a concrete deck, reinforced with steel bars, post or pre-tensioning tendons, which serve as the finished wearing surface and resist the abrasion of tires on surfaces. Some of these decks are exposed to rain and snow, and others are subjected indirectly to moisture carried on the undersides of cars. Moisture may also be associated with deck cleaning and maintenance activities. Deicing salts are also brought on the undersides of cars or are applied directly to the deck to melt ice and snow for improved traction. Virtually all deicing salts used in current road and highway maintenance contain chlorides [3]. Exposure to and effects of chlorides may worsen when the water stands on the deck surface. In offshore and marine areas, salty sand, salt-water spray, seawater, and prevalent high moisture conditions can also lead to serious corrosion problems.

The temperature of these structures follows seasonal and daily temperature cycles, although a temperature lag always occurs in the materials. Differences in temperature

along cross-sections of a reinforced concrete structure result in volume changes in the members, changes that are greater than those within enclosed structures. Such changes are frequently smaller in the plan dimensions and exist in an environment with more constant temperature, humidity, and moisture. Restraint of volume change can cause cracking of decks and floor slabs, beams and columns, which, if unprotected, may allow rapid ingress of water and chlorides leading eventually to deterioration [4]. When deicing salts are used, some of these salts become absorbed by the cover of the concrete. Under severe wetting, drying, freezing and thawing cycles, these produce high osmotic and hydraulic pressures with a consequent movement of water toward the coldest zone where freezing takes place. Damage will occur when the resulting tensile strain exceeds the tensile strain capacity of the concrete, which varies with the age of the concrete and the rate of application of strain. The extent of damage varies from surface scaling to complete disintegration as the layers of ice are formed, starting at the exposed surface of the concrete and progressing through its depth [5].

2.2 Common Observed Defects

2.2.1 Cracking

2.2.1.2 Common Cause of Cracking

Cracking of concrete occurs whenever the tensile strain to which concrete is subjected exceeds the tensile strain capacity of the concrete. The tensile strain capacity of concrete varies with age and with rate of application of strain. There are many mechanisms by which this strain may be generated within the concrete, such as drying shrinkage, expansion or contraction due to temperature change, and plastic or thermal shrinkage.

Cracking may also occur in the concrete from any number of causes. These causes can usually be classified in three major groups: (1) corrosion-induced cracking; (2) volume changes due to temperature change, and humidity change; and (3) structural cracking due to abrupt change in the geometry, members alignment. Structural loading, as a single standard of judgement of a cause of cracking, appears to be blamed too often. Structural behavior of a reinforced concrete member under loading induces tension that

may cause bending that produces flexural cracks, diagonal tension cracks, and anchorage bond cracks. Diagonal tension and anchorage bond cracking normally occur only at high load levels, and were once considered relatively unimportant, but there have been several reported failures. If diagonal tension or anchorage bond cracking does occur, most often it does not contribute to the cracking on the concrete cover surface. Flexural cracking is of most concern when it occurs from negative bending moments in the decks, joists, beams, and girders reinforced with deformed bars only [4]. Cracking can occur from tension induced by the expansion of the products of corrosion forming around the steel reinforcement. These cracks are often associated with delamination and spalling of the concrete [4].

Abrupt changes of geometry, such as the depth or the cross-sectional area, cause differential plastic settlement leading to cracking, or induce local stress concentrations which sooner or later may create cracks, e.g., ribbed slabs, trough sections, waffle slabs or voided slabs.

Drying shrinkage and decrease in temperature combine to produce a shortening of the concrete. When this volume change is restrained by other parts of the structure, cracks can form. The likelihood of crack formation from volume change is enhanced by the presence of geometrical discontinuity, such as construction discontinuities (construction joints), control joints, isolation joints (expansion joints) and the tensile stress already existing from bending moments. Cracks that occur in the surface of fresh concrete soon after being placed and while it is still plastic are called plastic cracking. Plastic cracking may also develop under certain conditions during construction if evaporation of water from the surface exceeds the bleeding rate of the water from the moist concrete. The control of plastic cracking is provided by adjusting the concrete mix or construction means and methods including curing.

If the concrete is sufficiently cured, the permeability of the surface layer of concrete may be increased fivefold to tenfold. The depth of the permeated layer depends on the nature of drying; however, this depth is often equal to or thicker than the concrete

cover. Wind and high temperature are very dangerous as far as early drying out of the concrete surface is concerned. Curing measures taken after first drying out of concrete are useless, because the hardening will scarcely continue after having been interrupted even once. Therefore, curing measures must begin immediately after concreting, and they must not be interrupted. Poor compaction or gravel pockets tend to increase the permeability of concrete to such an extent that protection of reinforcement no longer exists.

2.2.1.3 Flexural Cracking at Deck Top

The occurrence of flexural cracking at the deck top is one of the common types of cracks and is of particular interest in bridge decks and parking structures. It provides direct access for water where negative moment cracks in continuous T-beam extend through the entire slab thickness as shown schematically in Figure 2.1. Two basic approaches to the design of slab systems are used: (1) simple span systems (usually with precast or precast prestressed components), or (2) continuous span system (usually cast-in-place construction with reinforcing bars or post tensioning reinforcement). Many structural systems combine simple and continuous span construction and use both types of reinforcement [4].

A schematic drawing of the type of cracking and deformation expected in simple span flexural members is shown in Figure 2.3 and 2.4. A major advantage is that rotation at the ends of members can cause relatively wide cracks over the supports.

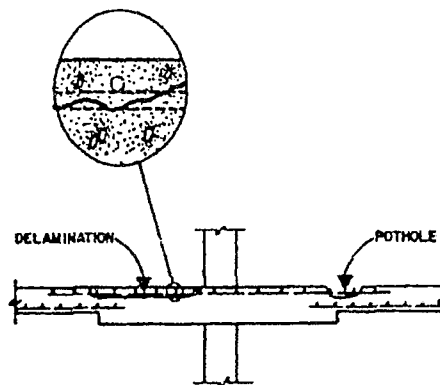


Fig. 2.1 Through Slab Cracks due to flexing of T – beam [4]

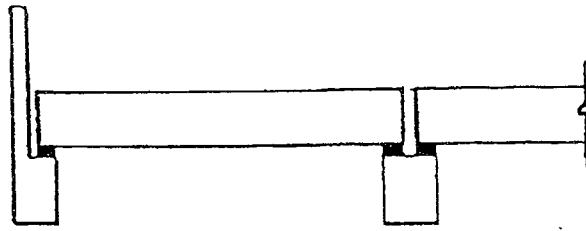


Fig 2.2 Schematic Simple Span Slab Construction [4]

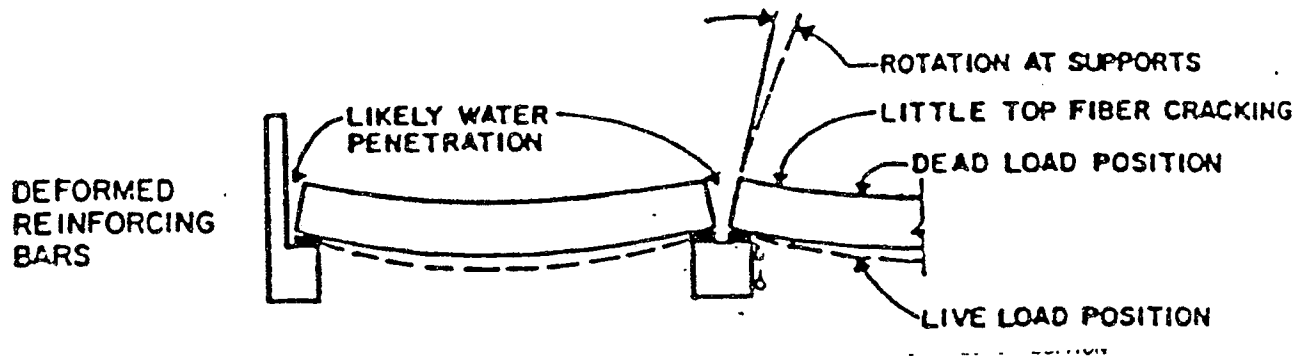


Fig. 2.3 Schematic Simple Span Slab Construction under gravity Loads (using deformed bar reinforcing) [4]

If these cracks are anticipated and a seal is provided, the seal must be properly sized, installed, and maintained; otherwise leakage can occur. Both cast-in-place and precast systems have similar advantages and disadvantages with the cracking at the deck slab top. Both cast-in-place and precast systems require careful evaluation of potential cracking and leakage along the side of the flexural members.

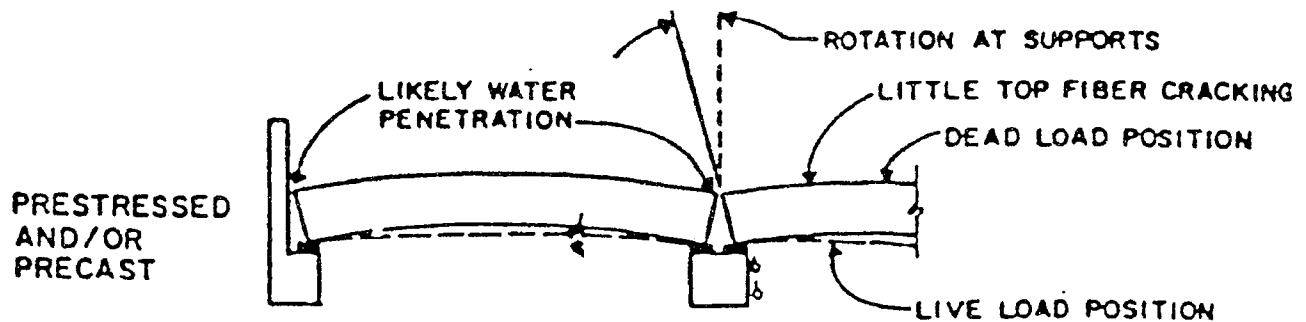


Fig. 2.4 Schematic simple span slab construction under gravity loads (using prestressed reinforcement) [4]

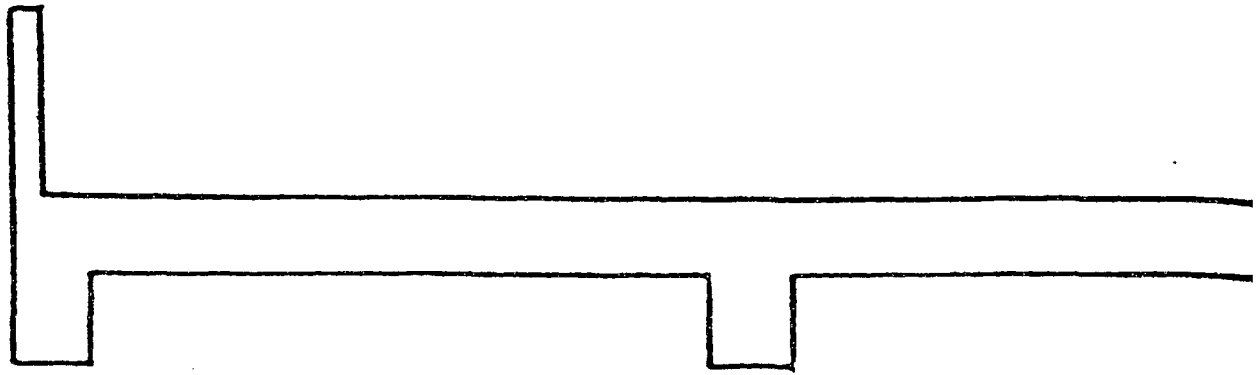


Fig. 2.5 Schematic Continuous span slab construction as cast [4]

A major advantage of continuous span construction, shown in Figure 2.6 and 2.7 is the elimination of the concentrated locations of rotation, which can cause water penetration problems. A major disadvantage is that top of slab flexural cracking shown in Fig. 2.6 frequently occurs due to the frequent negative bending moments. Top of slab, joist, beam, and girder flexural cracks can be substantially reduced under service load in some continuous post-tensioned construction as shown schematically in Fig. 2.7 [4].

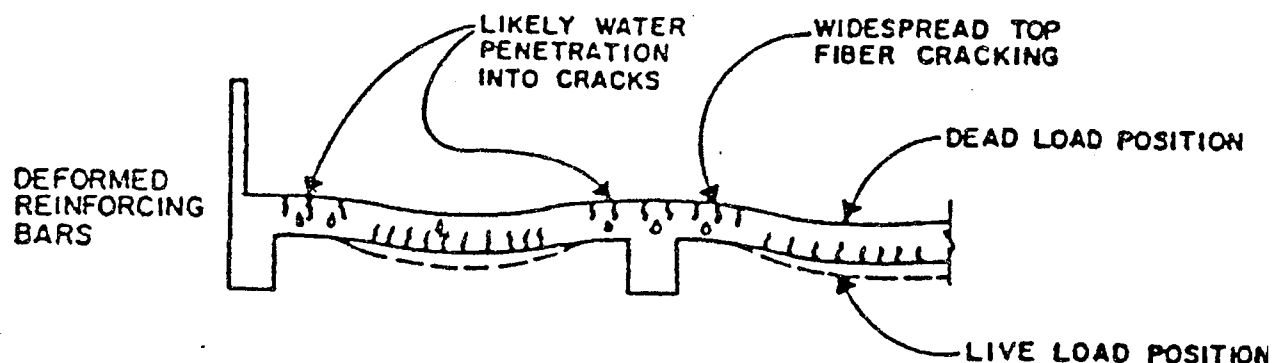


Fig. 2.6 Schematic Continuous span slab construction under gravity loads
(using deformed reinforcing) [4]

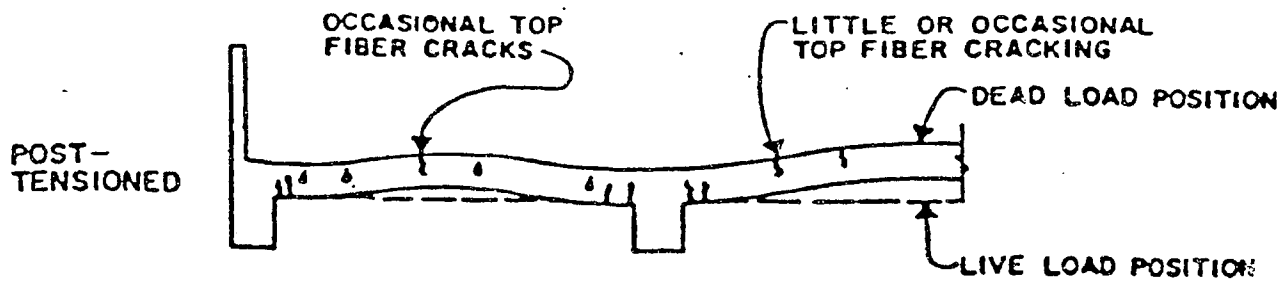


Fig. 2.7 Schematic Continuous span slab construction under gravity loads
(using post – tensioned reinforcing) [4]

2.2.1.4 Orientation of the Bar

For cracks that are commonly less than 1mm in width, the reinforcement bar orientation is of particular concern for the corrosion of reinforcement steel [6]. For cracks that are transverse to the reinforcement, localized corrosion is limited to about three bar diameters. If the concrete is of low permeability, then the corrosion reaction is in fact slow, and may eventually cease. However, if the cracks are in a longitudinal direction and coincide with the bar orientation, the passivity is lost at many locations. In the latter case, reinforcement corrosion will become very serious, and the concrete will lose its durability and deteriorate rapidly [6]

The corrosion process may result in a reduction of cross-section of the reinforcement and splitting of the concrete cover. If the cross-section is reduced, the load-bearing capacity of the steel decreases in a roughly linear fashion, whereas the elongation properties and fatigue strength may be reduced more substantially by a small reduction in the cross-section. This means that the latter two properties are much more sensitive to corrosion than the load-bearing capacity. Limitation of crack widths cannot reduce the corrosion risk under these circumstances [6].

One of the major common causes of longitudinal cracking in bridge decks is consolidation or settlement of plastic concrete. Cracks develop usually around reinforcement due to improper placing, finishing, consolidation, and movement of bars. Also voids and bleeding water under reinforcement can lead to cracks over the steel bars [4, 6]. Rapid setting of plastic concrete before adequate consolidation takes place is

another reason for longitudinal cracking. Weather conditions (sun, wind, and relative humidity) can cause rapid concrete setting and increase the tendency towards surface cracking. Concrete cover is the main factor in construction practice that controls surface cracking. Increased thickness of cover reduces the occurrence of longitudinal cracking as shown in Figure 2.8. Other factors that decrease the tendency to settlement cracking are decreased slump, control of rapid setting and evaporation, and proper finishing and curing [6.9].

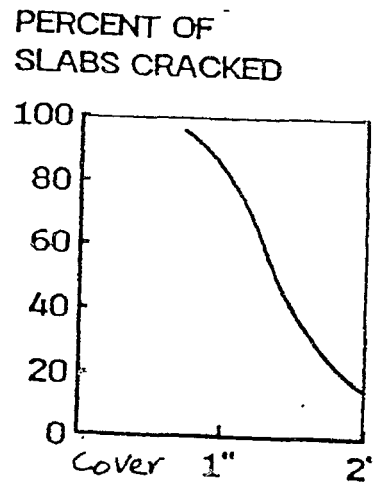


Fig. 2.8 Effect of cover on settlement cracking [6]

2.2.2 Spalling

2.2.2.1 Phenomenon of Spalling

Concrete spalling, also called delamination, is the final result of corrosion-induced pressure covered by the significant increased volume of corrosion products. When such fractures reach the surface, they allow the concrete to break away, leaving an open spall or pothole. The corrosion process is accelerated to many times its normal rate by the presence of chloride or road salt and plenty of moisture and oxygen [7].

Spalling is generally recognized as the most trouble some defect because the deck becomes weak, the reinforcement is exposed, and the riding quality and comfort decrease; moreover, the repair work is difficult. The bridge deck should not be left unattended, as these spalls can grow into complete deck failures that require the most

urgent attention. However, such failures rarely occur without prior warning, as evidenced in the common experience of noting hollow-sounding areas in the deck [8].

2.2.2.2 Mechanism of Spalling

Over a given reinforcement bar, fresh concrete has a tendency to segregate, and the particles, of various sizes, tend to flow to one side or the other of the bar. Plastic shrinkage, drying shrinkage, and thermal stresses find relief in this area by causing a crack, particularly if the steel is close to the surface and especially if the concrete is very wet and thus subject to considerable shrinkage. This crack over the top reinforcing bar, which is usually transverse to the traveled roadway, is very common in bridge decks. Salt-laden water can ingress through cracks and permeate through the uncracked concrete. Bleed water that is trapped under a surface crust creates planes of weakness that may cause early spalling [8].

Different concentrations of salt or moisture are sufficient to set up anodic and cathodic areas in a galvanic electrochemical cell and eventually cause a flow of corrosion current. Salt in solution provides an electrolyte, and oxygen in the water provides the oxidizing agent. The ferrous ions are later precipitated into rust on the anode. When the cracks fill with water and freezing occurs, even greater pressures are exerted. Passing traffic can create significant compressive stresses caused mainly by flexure, thereby inducing stress reversal and fatigue characteristics, with the result that the entire cover can be lost from this repeated activity [8]. Figure 2.9 shows different factors causing spalling during and after construction.

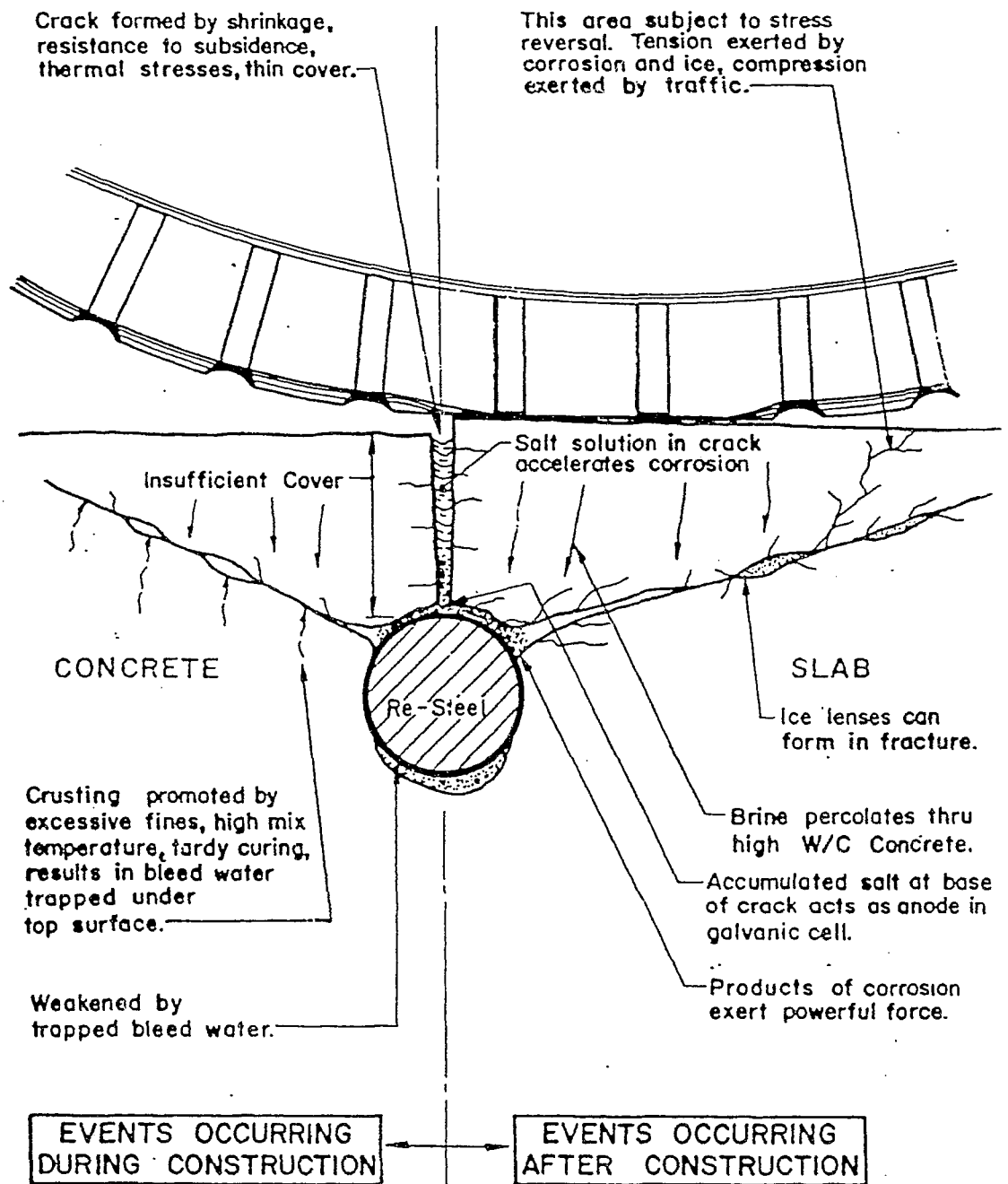


Fig. 2.9 Causes of Spalling during and after construction [8]

2.2.3 Scaling

2.2.3.1 Phenomenon of Scaling

Concrete scaling is a deterioration mechanism, the result of attacks on the mortar fraction of the concrete mix. It is characterized initially as a minor flaking and disintegration of the concrete surface. With passing time it progresses deeper into the concrete, eventually exposing aggregate, which breaks away. This contributes further to the process by exposing more paste to the elements. In extreme cases, apparently sound concrete can be reduced to gravel in a relatively short period of time [7].

Scaling can also be caused by freeze-thaw action in the absences of deicers. It can also be caused by chlorides without freezing. But scaling is especially severe when concrete is subject to freeze-thawing action in the presence of deicers. Scaling can be markedly reduced by air entrainment. It also can be significantly reduced by linseed oil treatment. But scaling can be virtually eliminated by the proper use of air entrainment in addition to linseed oil treatment where applicable. Scaling increases in concrete with a high water/cement ratio, but it is not related to spalling or deep cracking [8].

2.2.3.2 Mechanism of Scaling

When fresh concrete hardens, capillary pores are caused by the dissipation of water in the hydration reactions and by evaporating water. When water in a saturated cavity freezes, either the volume must expand (by 9%), or the excess water must be forced out of the cavity or the pore. In any system of voids, moisture tends to move from the larger voids to the smaller ones. Since the entrained air voids are far larger than the capillary voids, they remain essentially free of moisture. They are available as points of pressure relief. After thawing, the moisture is drawn from the entrained air voids to the capillary cavities by capillary action. If enough unfilled entrained air voids are present, disruptive hydraulic pressures will not develop. A low water/cement ratio paste will have smaller and fewer potentially vulnerable capillary cavities and will therefore be more resistant to frost action [10].

Placing salt on pavements for ice removal will increase the concentration of salt in the capillary voids near the surface of the pavement. As the salt solution freezes, a greater concentration of salt results and osmotic pressure is built up in the capillary cavities. This increase of pressure may be sufficient to cause a rupture of the cement gel near the surface of the deck and consequently cause scaling.

Deicing salt not only creates additional forces through osmosis, but also provides an additional source of surface moisture in freezing weather by melting the ice and snow. As deicing salt melts snow and ice, the temperature immediately below the surface is reduced significantly because of the comparatively large heat of fusion of ice. This may cause a damaging temperature drop in the saturated zone immediately beneath the surface [10].

2.2.4 Joint Deterioration

The two most common provisions made for providing crack control, or relief of restraint in concrete slabs, are control joints and expansion joints. Such joints have long been a source of maintenance problems. Joints on supported slabs must be sealed against water leakage and intrusion. Both situations are damaging to the joints system e.g., repeated water pounding stained the concrete surface, and can cause the spalling, which later transform in to the steel reinforcement corrosion.

Construction joints deteriorate for several reasons usually associated with the failure of the sealant or failure of the adjacent concrete e.g., incompatible sealant material, wrong alignment of joints, and improper installation. Joint sealant may not have the required degree of flexibility, bond strength, or durability for a particular application. If concrete adjacent to the joint is not sufficiently durable, then local scaling will cause joint sealant failure.

Expansion joints are also susceptible to premature deterioration. The most common causes of early deterioration are inadequately designed joints or sealant material specification may result in spalling of concrete adjacent to the joints. The full range of

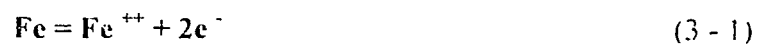
possible different temperature that concrete may be expected to experience should be taken into account in the specification for expansion joints. There is no single expansion joint that will work for all cases of temperature differential [7].

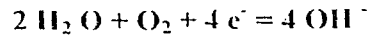
3. CORROSION OF STEEL IN CONCRETE

3.1 Effects of Carbonation

Due to carbonation of concrete or by the action of chloride ions, the passive film may be destroyed locally, or over larger surface areas. A third mechanism is a reduction of alkalinity due to the leaching out of alkalis by flowing water. In general practice, this may happen in the area of weak point of the structure (e.g., leaky construction joints and wide cracks), in combination with poor concrete quality (gravel pockets, high w/c ratio). If the pH of concrete drops below 9 at reinforcement, or if the chloride content exceeds a critical value, the passive film and the corrosion protection will be lost. Corrosion of reinforcement is possible if sufficient moisture and oxygen are available. This can be assumed to be the case for most structures in the open air. The principles of passivation and depassivation hold true for both normal reinforcing and for prestressing steel [5, 22].

Electrochemical action due to the formation of local electrolytic action or galvanic cells along the surface of rebars is generally considered to be the cause of most corrosion-related structural distress in concrete [11]. The corrosion process can best be understood by considering an example of a simple electrochemical cell or the process that takes place in a flashlight battery [1]. Each has an anode, in which electrochemical oxidation takes place; a cathode, in which electrochemical reduction occurs; and an electrical conductor; and an aqueous medium is present. Any metal surface on which corrosion is taking place is composed of anodes and cathodes electrically connected through the body of the metal itself. Reactions at the anodes and cathodes are broadly referred to as "half-cell reaction". At the anode, which is the negative pole, iron is oxidized to ferrous ions:





(3 - 2)

3.1.1 Oxygen Availability in Concrete

All deterioration processes require water: The important factor is the moisture state in the concrete rather than that of the surrounding atmosphere. Under steady conditions, these will be constant, but under varying conditions concrete takes water from the environment more rapidly than it loses and so the internal average humidity tends to be higher than the average ambient humidity. The availability of oxygen (dissolved) in chloride-effected concrete is one of the main factors that encourage the corrosion of steel. Figure 3.1 shows that the rate of oxygen diffusion through water-saturated concrete depends on the thickness and quality of concrete [13], as cited in [1]. Oxygen diffusion in concrete takes place mainly through the capillary pores, damaged areas and microcracks. Therefore the rate of oxygen diffusion through concrete is also significantly affected by the degree of saturation of concrete with water [1]. The principle also holds true where members are subject to wetting and drying cycles: frequent wetting, as in ideal regions, can maintain concrete in saturated condition. [14].

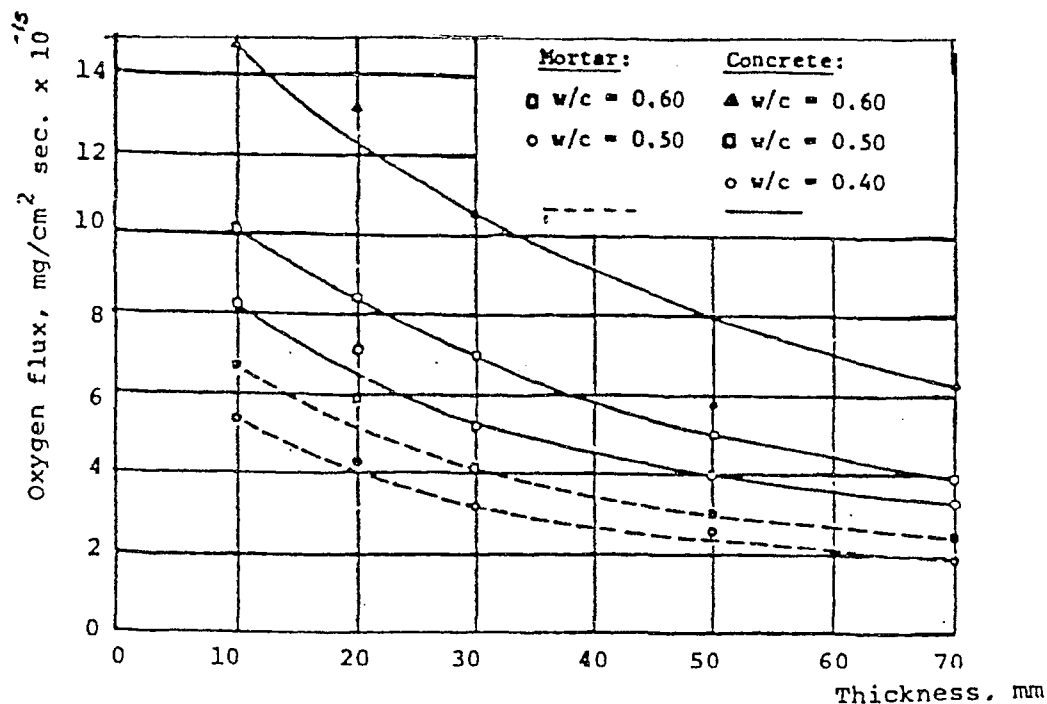


Fig.3.1 Effects of water/cement ratio and thickness on the diffusion of oxygen through mortar and concrete [14]

Since it is the concentration of dissolved oxygen that is important, all factors affecting the solubility of oxygen would also affect its availability. The effect of salt on the corrosion rate has been demonstrated by Griffin and Henry, Figure 3.2 [1].

Corrosion increases as the sodium chloride concentration is increased until a maximum value is reached. Beyond this, the rate of corrosion decreased despite the increase chloride ion concentration. This change in relationship between corrosion and sodium chloride concentration is attributed to the reduced solubility and diffusivity of oxygen, and therefore, affects the availability of oxygen to sustain the corrosion process. This process describes corrosion in a salt solution; however, the availability of oxygen in wet concrete may be different. Problems due to corrosion of embedded steel have seldom been observed in concrete structures, which are continuously submerged, even if it is in seawater [1].

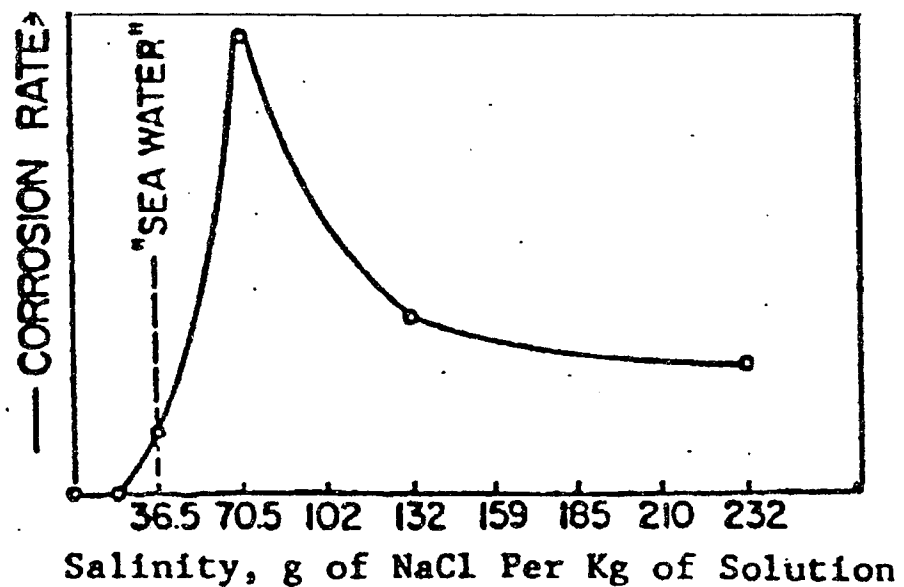


Fig.3.2 Effect of construction of sodium chloride on corrosion rate [15]

3.1.2 The Effect of Chloride Ions

The entry of chloride ions in reinforced concrete can cause steel corrosion if oxygen and moisture are also available to help this reaction [16,17]. No other contaminate is documented as extensively in this study as a cause of corrosion of steel in concrete.

Chloride ions may be introduced into concrete in a variety of ways. Some are intentionally included as an accelerating admixture, there may be accidental inclusion as contaminants on aggregates, or penetration by deicing salts, industrial brines, marine spray, fog or mist. Any diffusion of chloride ions into concrete is accompanied by both physical absorption and chemical binding. These effects reduce the concentration of chloride ions at a particular site and hence the tendency for inward diffusion is further reduced [19], as cited in [1]. This is also illustrated in Figure 3.3.

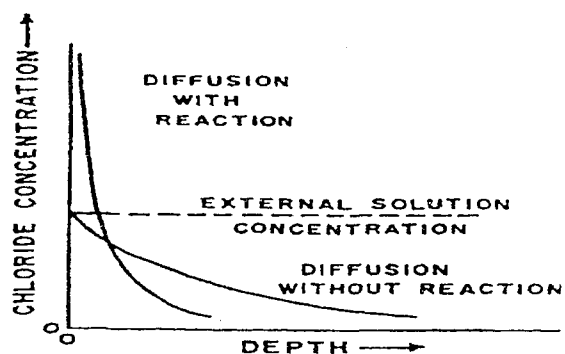


Fig 3.3 The gradient of total chloride concentration depth depends on whether or not chemical reaction occurs with the cement [19]

There are three theories used currently to describe the role of chloride ions in the corrosion process: (a) The oxide film theory. In this theory, it is believed that an oxide film on the steel bar surface provides the passivity and thus protection against corrosion. The chloride ions are believed to penetrate the oxide film on steel through pores or defects in the oxide film in a way easier than other harmful ions. In an alternative way, the oxide film may be colloiddally dispersed by the chloride ions, thus facilitating the penetration and ingress of chlorides.

(b) The adsorption theory. In this theory, it is believed the steel surface adsorbs chlorides, oxygen and hydroxyl ions. The iron ions are dissolved due to hydration of metal ions aggravated by chloride ions.

(c) The transitory complex theory. This theory postulate that a soluble complex of iron chloride is formed [1], as cited in [1], in a competition between chloride ions and hydroxyl ions to react with the ferrous ions. This reaction takes place at the anode where

the soluble complex of iron chloride diffuses away from the parent metal, thus destroying the protective ferrous oxide layer and promoting the process of corrosion. This complex is dissolved again and breaks down at some distance from the electrode. Iron hydroxide is precipitated, and the chloride ion is free again to start a similar cycle or reaction, permitting corrosion of the anode to continue. In a sample of broken concrete with active corrosion, a light green semisolid reaction product is usually found close to the steel surface, which turns to black when exposed to air and finally the usual rust color is observed [1].

More ferrous ions are transported away from the anode and react with oxygen when available to form higher oxides. The corrosion process is not stifled and continues as long as all the reaction components are available. The product of corrosion is many times greater than the volume of the original ingredients. When iron oxides are transformed to higher oxidation states, they expand and produce internal pressure. When the tensile stresses due to internal pressure exceed the concrete tensile strength, cracking occurs. It is believed also that the formation of iron chloride complexes may also promote and increase the internal pressure [1].

3.1.3 Rate of Corrosion and pH

Figure 3.4 shows the effect of pH of concrete on the rate of corrosion providing that oxygen is available at room temperature. Corrosion rate of reinforcement decreases with the increase in pH. Concrete is considered an excellent protective medium for reinforcing steel from corrosion [1].

It has been mentioned that steel become passive in calcium hydroxide solution due to the formation of an impervious layer of ferric products on the steel surface. If for some reason the hydroxyl ion concentration is reduced, the protective layer would be disrupted and corrosion would proceed. Shalon and Rapheel [21] found that the minimum pH for inhibition of steel corrosion varies from 11.5 to 12.75, depending on the nature of the corrosion and the degree of aeration.

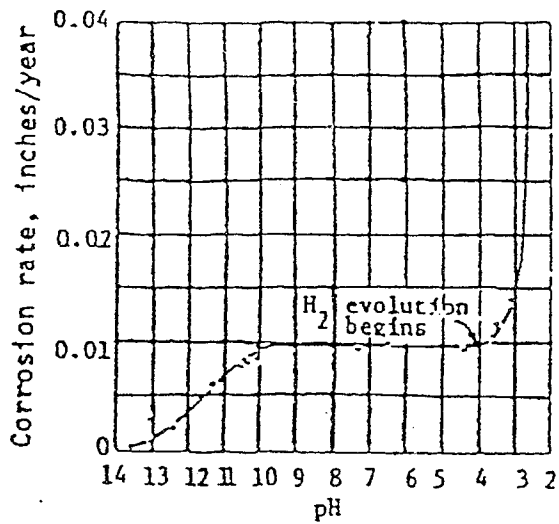


Fig. 3.4 Effect of pH on corrosion of iron in aerated soft water at room temperature [11]

There are two general mechanisms that may destroy the highly alkaline environment [19].

- (a) Reduction in concrete alkalinity due to leaching of alkaline substance with water or partial neutralization by reaction with carbon dioxide (carbonation); and by
- (b) Electrochemical action prompted by chloride ions in the presence of oxygen.

Boyd and Tripler [22] have pointed out that the pH at a crack in concrete may drop to between 6 and 7 as result of leaching by a sodium chloride solution. Crumpton and Bukovatz [23], as cited by [26], have reported after measurements made under field and laboratory conditions a pH of below 3 and often below 1 in localized areas adjacent to the reinforcing steel, whereas only 1 mm and 2 mm away the pH was usually 12 or more. The reduced pH is believed to be due to the formation of hydrochloric acid, which forms when hydrogen ions released at the cathode react with chloride ions in the water.

3.1.4 Corrosion Rate Control

It was shown in Section 3.1 that both cathodic and anodic reactions are necessary for the corrosion process to occur. Different corrosion conditions were plotted, on the same graph, the log of the corrosion current (i) versus potential (E) curves by ACI committee 222 [1]. The potential (E) obtained by polarizing each half cell with an

auxiliary counter electrode in the absence of the corroding sample would be that at which the two I versus E curves for both cathode and anode intercept. The absolute value of the current at the intercept is equal to the corrosion current [1].

Figure 3.5 illustrates the cathodically controlled rate of corrosion where the cathodic process is the slower process. Conversely, Figure 3.6 illustrates the anodically controlled rate of corrosion where the anodic process is slower. Corrosion rate of reinforcement in the concrete environment could be controlled by cathodic diffusion and/or developing a high resistance path for the corrosion current. In case of cathodic diffusion, where the rate of oxygen diffusion through the concrete determines the rate of corrosion, two different rates of oxygen diffusion are shown in Figure 3.7. The other controlling factor, which is the development of a high resistance path, may be of greater importance when anodic and cathodic areas are a considerable distance apart.

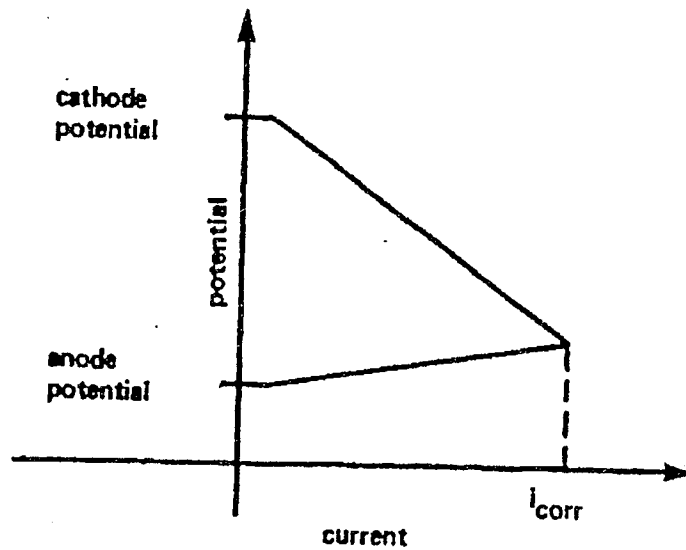


Fig. 3.5 Cathodic Control [1]

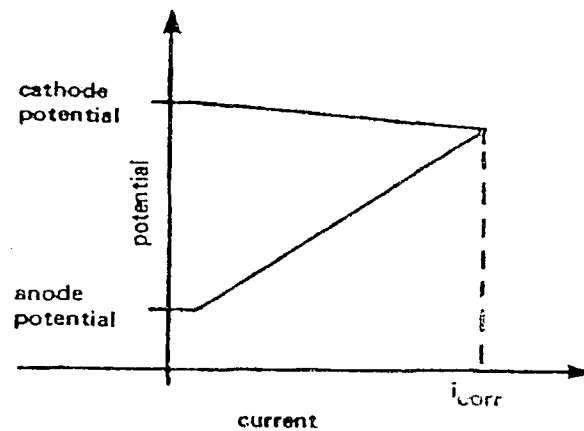


Fig. 3.6 Anodic Control [1]

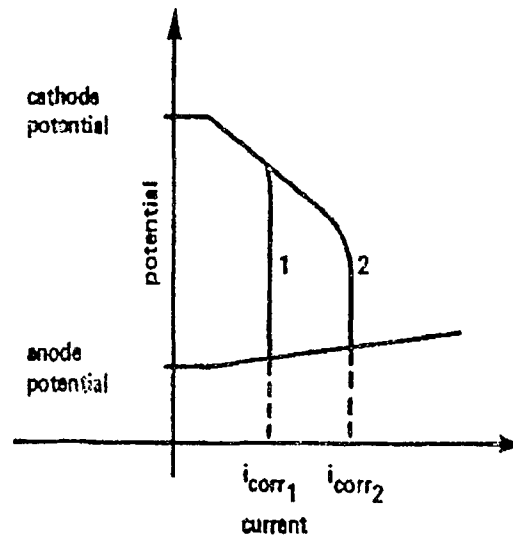


Fig.3.7 Cathodic diffusion control [1]

3.2 Effect of Concrete Environment on Corrosion

3.2.1 Types of Cement

The Variation in cement composition and its fineness, or both result in difference in the types of cement, and as a result, not all types of cement provide the same alkalinity (pH). The integrity and protective quality of oxide film on the steel depend on the high alkalinity of the chemical environment normally present in concrete [1].

Pressler et al [24] reported that a well hydrated portland cement may contain from 15 to 30 percent calcium hydroxide by weight of cement. This is usually sufficient to maintain a solution at a pH of about 13 in the concrete independent of the moisture content [1]. The hydration of portland cement consists predominantly of two kinds: relatively large crystals of calcium hydroxide $[Ca(OH)_2]$ and very small (colloidal) particles not clearly stated hydrated calcium silicate compounds, often indicated in abbreviated form as C-S-H gel [57]. Crystal is generally ranging in size from less than 1 μm to about 100 μm , with an average diameter of about 15-20 μm . The average composition of the C-S-H gel in most concrete is roughly $CaO \cdot 2SiO_2 \cdot 2H_2O$. Small amounts of several different kinds of hydrated calcium aluminate sulphates and other products may also occur.

Spellman and Stratfull [25] showed that adding a pozzolan to the portland cement did not adversely affect the performance of the steel in concrete that was partially immersed in a saturated salt solution. The partial replacement of cement by pozzolans improves the overall quality of concrete and produces stable calcium silicate hydrates, which has good resistance to salt attack. Also, the pozzolans mixture can be effective for the following reasons: (i) Improved cohesion and minimization of segregation; (ii) Lower sensitivity to the control of the water content; (iii) Provision of adequate early strength (iv). Improvement in durability [5].

The alkalinity of a concrete structure may be lowered in a number of ways even for cement with a large alkaline reserve. Reduction of alkalinity by leaching of soluble alkaline salt with water is a common example. Carbon dioxide present either in air or dissolved in rainwater can cause partial neutralization by reaction with the alkaline concrete; thus carbonation is another obvious process that reduces concrete alkalinity [1].

3.2.2 Water Saturation

It was shown in the previous section that the degree of saturation of concrete with water affects the rate of oxygen diffusion into concrete. The rate of carbon dioxide diffusion into concrete is substantially reduced at high moisture content and hence the

rate of concrete carbonation. On the other hand, moisture penetration is the means by which exterior substances such as chloride salts, carbon dioxide, and dissolved oxygen may gain access to the reinforcement [26].

In concrete, gel and capillary pores are important for transport. Immediately after mixing, only capillary pores exist, and they are completely filled with water; with progress of hydration, the gel pores replace the capillary pores and the porosity distribution is shifted to smaller values. The significant changes in the water saturation of the pores occur close to the surface: mostly capillary pores respond to the change in environmental conditions. All these internal changes are factors that influence transport of radon through concrete and have to be taken into account when modeling radon release [47].

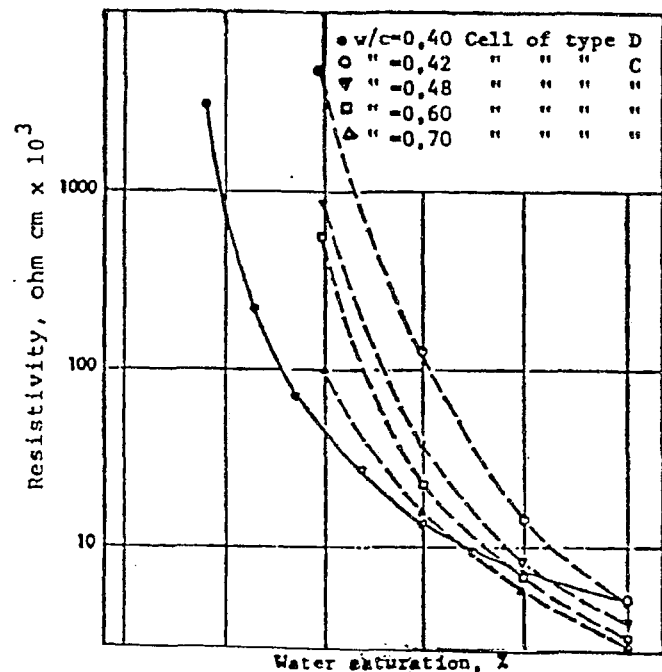


Fig.3.8 Effect of water saturation on resistivity of concrete [27]

Electrolytic conduction in concrete is confined to ionic movement in the evaporable water phase in capillary and gel pores. Therefore, the moisture content of concrete is an important factor affecting the electrical resistivity of the concrete [1]. Prolonged drying of initially water-saturated concrete results in the electrical resistivity

increasing from about 7×10^{-3} ohm - cm to about 6000×10^3 ohm cm (Fig. 3.8) [27]. The values of resistivity above which corrosion-induced damage are unlikely, even in the presence of chloride ions, oxygen and moisture content, has been considered to be 7×10^3 ohm - cm [28].

3.2.1 Carbonation

Concrete is a porous material, and the carbon dioxide (CO_2) in the air may therefore penetrate the pores to the interior of the concrete. A chemical reaction will take place with the calcium hydroxide.



As it is mainly the Ca (OH)_2 that causes the high pH of concrete to develop, the pH will drop below 9 after the concrete has been totally carbonated.

The action of CO_2 is restricted to a thin surface layer. Maximum carbonation rates are observed at about 50 percent water saturation [29], as cited in [5]. Ca (OH)_2 carbonates to CaCO_3 , but other cement compounds are also decomposed [5].

A severe consequence of carbonation is the reduction of alkalinity to the extent that the passivity of embedded steel is affected. For high-quality concrete, carbonation is normally not a problem unless concrete has cracked. Localized corrosion of the reinforcement in cracked concrete may be accelerated due to carbonation. In addition to their electrochemical influence on the initiation and rate of corrosion, chlorides also can cause physical damage to the concrete surface. This is due in effect to "thermal shock" resulting from accelerated freeze-thaw cycles. Progressive surface spalling can occur, reducing or eliminating cover to steel reinforcement.

On the other hand, some degree of autogenous healing can take place in the presence of moisture and carbon dioxide in the cracked concrete [24]. Autogenous healing is another unique characteristics of Pagan's natural pozzolan, as it has inherent ability to heal or re-cement cracks within the concrete by means of its continuation of pozzolanic reaction with the calcium hydroxide freed from the hydration of portland

cement. This autogenous healing mechanism mends the structures by filling the gaps inside the hardened concrete. (Concrete International)

The concentration of chlorides to promote corrosion of the embedded reinforcement is affected by the concrete's pH. Given the pH of fresh concrete (12.7 - 13.2) a threshold level of about 7,550 - 8,000 ppm is required to start corrosion of embedded reinforcement, but if the pH is lowered to 10.5 - 11.5 (still sufficient to turn phenolphthalein solution purple) the chloride threshold is significantly lower, at or below 100 ppm.

4. CONCRETE DESIGN AND CONSTRUCTION PRACTICE

4.1 Structure of Concrete and Permeability

The risk of corrosion of reinforcing steel should be minimal in a well designed reinforced concrete structure containing a sufficient depth of good quality concrete cover that has been properly placed and compacted. The concrete cover provides both chemical and physical barriers to corrosion [53].

The chemical barrier is the high alkalinity of the concrete pore water solution, which ordinarily has a pH value of about 13. This enables the formation and maintenance of permanent protective passivating film on the surface of the steel. The physical barrier is the density and impermeability of the concrete cover, which limits the diffusion of oxygen toward the steel and thus may block the corrosion reaction, even if the passivating film has been disrupted [57].

Heterogeneous chemical reaction between a liquid and a solid or gaseous phase constitutes the basis of concrete deterioration processes. The deterioration of concrete may be caused by either the aggressive environment to which the concrete is exposed or by internal causes within the concrete composition itself. The extent of damage produced by external causes depends largely on the quality of concrete. Permeability is believed to be the most important property of concrete that facilitates corrosion of the reinforcement [19, 30, and 31]. Increased water/cement ratio produces a decrease in the gel/space ratio, thus increasing the volume and size of large pores and therefore permeability. High permeability concrete can become saturated with water relatively easier than concrete with low permeability [5]. When concrete with high permeability becomes saturated its electrical conductivity relatively increases. Also, the ingress of chlorides, oxygen and carbon dioxide to the reinforcing steel will be relatively easier [26].

Transport channels are formed by a system of pores and fissures of highly diverse dimensions, shapes and character of mutual bonds and are distinguished by an extensive inner surface. These characteristics of transport courses largely determine the intensity of reactions of the external medium with concrete during its deterioration. These processes take place on the outer as well as on the significantly larger inner surface of the pore structure of the concrete [57].

Concrete permeability depends upon numerous factors including air entrainment, cement/aggregate ratio, water/cement ratio, aggregate grading, consistency, degree of compaction, absence of bleeding and curing procedure. Lowering the water/cement ratio and increasing the degree of hydration will increase the "gel/space" ratio, thus reducing the volume of capillary pores and therefore permeability.

In an environment where the structure is exposed to chloride ions, the concrete should be made with the lowest water/cement ratio consistent with achieving maximum consolidation and density. The effects of water/cement ratio and degree of consolidation on the rate of ingress of chloride ions are shown in Figure 4.1 and 4.2 [32], as cited in [1]. If macro cells, which may cause rapid corrosive attack on the steel bars in concrete, are established in response to inhomogeneities in the cement paste concrete, salt concentration, aeration, and permeability throughout, the concrete will set up electrochemical activity [26].

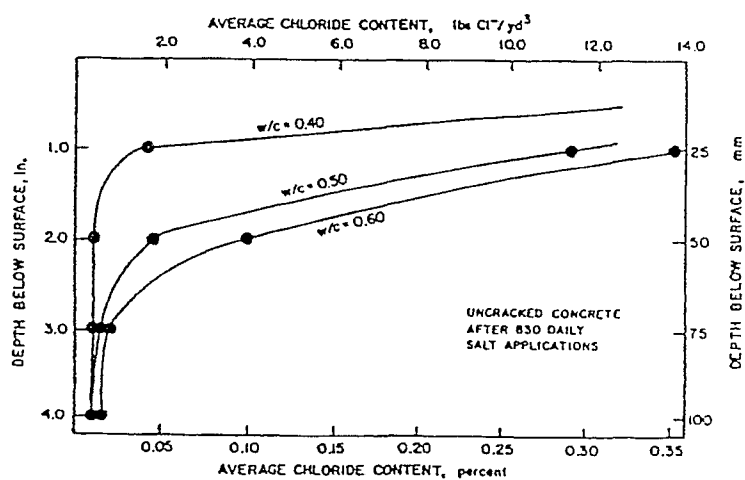


Fig.4.1 Effect of water/cement ratio on salt penetration [32]

4.1.1 Air Entrainment

The air-entrained concrete is considered one of the major successes in concrete technology. There are two different types of deterioration due to internal cracking and surface scaling, and freezing-thawing cycles. The main factor influencing the frost resistance of concrete, as shown by investigations over the last few decades, is the content of air in the hardened concrete introduced as a result of the foaming effect of air-entrainment additives added to the concrete mix. At present the production of concretes with high and guaranteed frost resistance is invariably ensured by using structure-forming, air-entraining or gas-liberating additives. The air entrains work in hardened concrete like artificially generated porosity (spherical pores) filled with air and separated by barriers of hardened cement of definite thickness. These spherical pores act like sealed air pores. In the process of freezing and thawing air pores are gradually and slowly filled with water, and it is important that the degree of critical water saturation is not attained in one winter season.

In such cases, the initial state of water saturation is restored in the summer period and the concrete reverts to the original phase condition of the hardened cement, strength and frost resistance. However, there are other important benefits of entrained air in both freshly mixed and hardened concrete [33]. Since, for good quality concrete, the presence of an adequate system of entrained-air voids is the only basic requirement to provide space for expansion of pore water upon freezing due to freezing-thawing cycles, the basic frost durability problem (excluding deicing salt scaling) The selection of a specified air content for (5% - \pm 1%) in the formwork, the air - void spacing factor of 0.2 mm and a specified surface of 25mm^{-1} represented the best practice In normal strength concretes, the data available indicate that the dosage of the air-entraining agent is the most

important parameter that controls the value of the air void spacing. As the data indicate, a relatively low dosage may be sufficient in certain cases, the lower required dosages of air - entraining admixture (AEA) typically occurred with the higher dosages of water reducing admixtures (WRA). Air entrainment will dramatically improve the durability of concrete exposed to moisture during cycles of freezing and thawing. Air entrainment is introduced by using an air-entrainment admixture during mixing to change the surface tension of fresh concrete ingredients. The spacing and size of the air void system are important factors contributing to the effectiveness of the air entrainment in concrete.

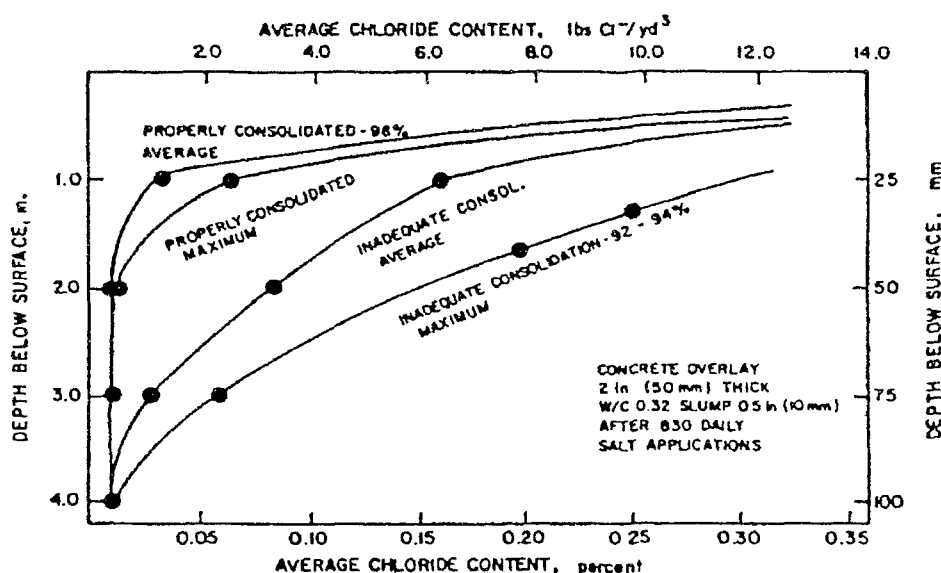


Fig. 4.2 Effect of inadequate consolidation on salt penetration [32]

Entrained air improves the quality and workability of concrete, and allows, even with a lower water/cement ratio with the same quality and workability. Bleeding and segregation are considered the major defects that happen during construction and which greatly affect concrete durability. The finely divided air void system acts to increase the strength of the cement paste between air bubbles due to a lower water/cement ratio, thus improving the freezing-thawing resistance [14]. In cases where concrete is exposed to deicing salts, the resistance to freezing-thawing damage and surfacing scaling is significantly improved by the use of intentionally entrained air [34]. Air entrainment

enhances the protective quality of concrete against corrosion through lowering its permeability.

4.1.2 Water/Cement Ratio

As noted earlier, the designers always want to use higher strength concrete than in the past, and this requires special attention and care to the mixture proportions. The high strength concretes can be achieved by the use of strong and good quality crushed stone aggregate, higher cementing material contents and a lower water/cement material ratio [57]. The water/cement ratio also exerts a significant influence on frost resistance. Concrete prepared from mixes of various workabilities and compacted by different methods shows a direct correlation between water content and frost resistance, which also depends on the volume of hardened cement since destructive stresses arise in it.

The major cause of low water/cement ratio is not only the concrete strength, but also other important properties of both freshly mixed and hardened concrete. For hardened concrete, the gel/space ratio is increased with low water/cement ratio, thus increasing the concrete strength and impermeability. In fresh concrete with low water/cement ratio, bleeding is reduced, therefore increasing concrete impermeability. The gel/space ratio is a function of water/cement ratio and the degree of hydration [57]. Using a water/cement ratio less than specified in the mix design allows the gain of high gel/space ratio at early ages or in cold weather [14]. The increase in strength of concrete may extend the time before corrosion-induced stresses cause cracking of the concrete.

The importance of impermeability in providing a protective environment against corrosion of reinforcement has been discussed in Section 4.1.1. The use of superplasticizers to reduce the water/cement ratio is also advantageous in producing concrete with less segregation and bleeding. There is no direct influence of a superplasticizer on shrinkage and creep, but as it reduces the water/cement ratio, shrinkage and creep are in turn reduced [5].

4.2. Bleeding

4.2.1 Nature and Causes of Bleeding

Bleeding is a form of segregation in which some of the mixing water tends to rise to the top surface of freshly placed concrete during the consolidation process. It can be expressed quantitatively, as the total settlement of freshly placed concrete is usually slight and would hardly be noticed, but the appearance of the accumulated layer of water on the surface is usually observable. The amount of bleeding water tends to be proportional to the settlement of solid constituents of freshly placed concrete under gravity forces [9].

For concrete treated to retard the setting time, bleeding and settlement are terminated due to the higher specified surface area of cement as a result of the hydration process. When the setting time is relatively shorter, bleeding and settlement are arrested mechanically by bridging the inter-particle gaps with hydration products [11]. The structure of the hardened concrete is affected to a large degree by the initial framework of the cement paste established at the time of setting [15]. It should be mentioned here that the destruction of fresh concrete structure early in a stage of hardening does no harm to the concrete quality. Concrete may be improved by re vibration as long as the mixture can be completely reconsolidated [9].

Normal bleeding is a characteristic of the flocculent state of the fresh concrete in which the interior particle attraction forces are balanced. Bleeding takes place due to establishment of the flocculation forces. Figure 4.3 indicates that the amount of bleeding increases proportionally with the increase of the water/cement ratio of the concrete mix.

At high specific surface area of cement grains (fineness), the average distance between particles is smaller with stronger cohesive forces, and accordingly normal bleeding will be limited [9]. Normal bleeding is an indication that inter-particle forces are strong enough to achieve adequate cohesion to the cement paste; the presence of channels is an evidence of partial disruption of the paste matrix [9].

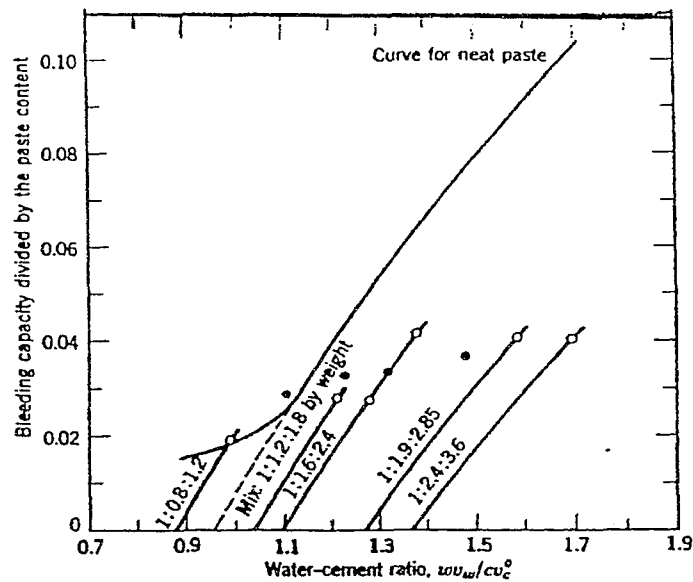


Fig.4.3 Relation between bleeding and water/cement ratio [9]

4.2.2 Factors Affecting Bleeding

It would be expected that the amount of bleeding water would be increased with an increase in the ambient temperature. Powers [9] considered the bleeding to be a phenomenon of fluid flow through a permeable body and that the bleeding rate will increase with the decreased viscosity at high temperatures. However, an increase of temperature can lead to less amount and rate of bleeding, and even early termination because of the associated early setting of the cement paste. In concrete bridge decks and slabs where there is more dissipation of heat of hydration, bleeding is usually completed before early setting of concrete takes place. The effect of temperature on bleeding is more pronounced by its influence on the time of setting than on the viscosity of water [9].

The increased water content of the concrete mix will increase bleeding as described in the previous section. Grading of aggregate has no direct effect on bleeding, but as it affects the required water content, a suitable grading can contribute to a decrease in bleeding [14].

The presence of air entrainment is very beneficial in reducing bleeding. The air bubbles tend to keep the solid particles in suspension, which reduces settlement and water expulsion. The cement grains appear to plug the surface of air bubbles, which clog water

channels in fresh concrete. The presence of entrained air improves workability with a low water/cement ratio because it acts as fine aggregates with very low surface friction and considerable elasticity; a reduction in sand content is accompanied which reduces the water content and thus bleeding [5].

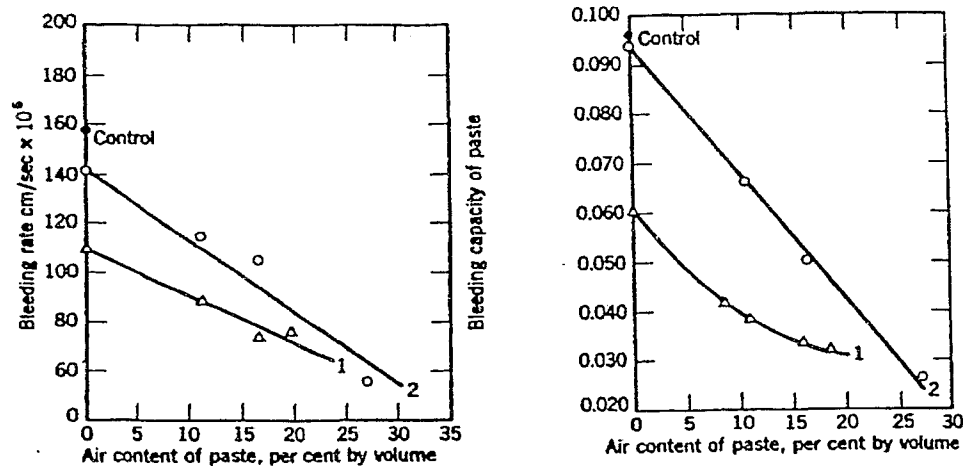


Fig. 4.4 Bleeding rates of pastes with various amount of entrained air [9]

Figure 4.4 shows the relation between air content and amount and rate of bleeding. The partial replacement of cement with pozzolanic material such as fly ash improves workability and fluidity of the freshly mixed concrete without increasing its water content [5].

Concrete chemical admixtures have different effects on bleeding. Accelerators tend to decrease the time of setting, thus reducing bleeding. Retarders would appear to increase bleeding as they increase the time of setting, but most retarders are water-reducing agents at the same time, which act to limit bleeding.

The use of superplasticizers improves workability with very low water content, thus reducing segregation and bleeding with a more cohesive mix. Superplasticizers disperse the cement agglomerates normally found when cement is suspended in water. They are absorbed on the surface of cement grains and fine particles, causing them to become mutually repulsive as a result of the ionic nature of the superplasticizers. They also maximize the negative charge in the chemical layer surrounding the cement grains.

and they have some retarding action in setting time as a side effect, but this action is of short duration [5, 14]. Concrete in deep forms will bleed more than in shallow members, like slabs and bridge decks. This will result in density gradient from the bottom to the top of the concrete [9].

4.2.2.1 Consequences of Bleeding

When horizontal-reinforcing steel interferes with settlement of freshly placed concrete, a layer of water forms under each bar. When water is absorbed by the hardened concrete, a permanent space is left under the bar as shown in Fig. 4.5. Linear depressions and settlement cracks along the length of rebars may develop, inviting rapid corrosion [4]. Zones of weakness may be formed in the arches of unstable fresh concrete between horizontal bars. This will lead to surface scaling loss in concrete cover over reinforcement [9].

Permeability of concrete increases with bleeding since capillaries and channels left by water is oriented in one direction. Permeability is considered the first cause of concrete damage and deterioration; therefore it is vital to concrete quality to avoid bleeding-induced permeability [5].

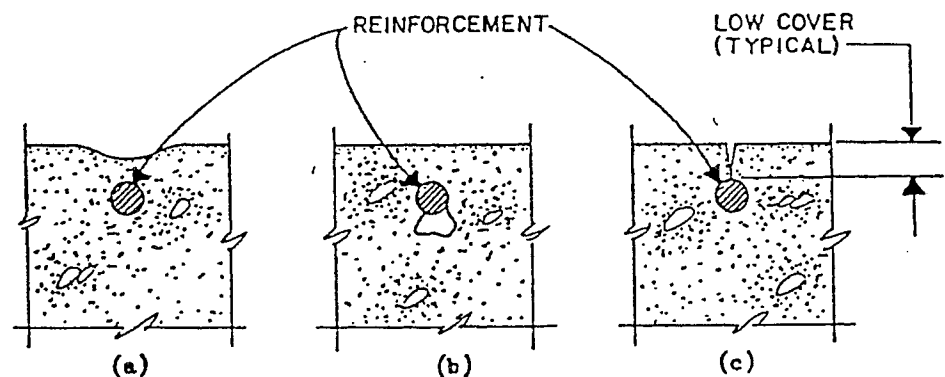


Fig.4.5 Formation of linear depression and cracks along reinforcement bars [4]

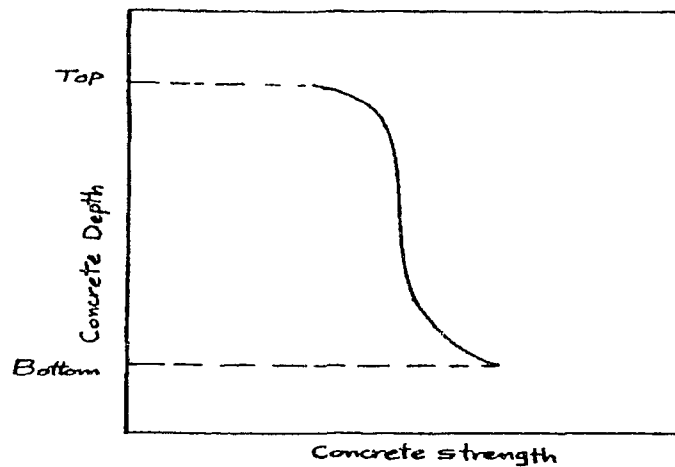


Fig.4.6 Effect of bleeding on concrete strength along the depth of slab [14]

As mentioned above, bleeding will result in a density gradient from bottom to the top of concrete. Accordingly, there will be a gradient in concrete strength along the thickness of concrete member. This is shown in Fig. 4.6.

4.3 Cover Over Reinforcement

The time required to depassivate the steel surfaces in reinforced concrete and thus start the corrosion reactions, and the rate at which these reactions will take place, both depend on the nature of the concrete cover provided. The connection between relative corrosion and the thickness of concrete cover over reinforcement and concrete quality is shown in Figure 4.7 [6].

The height of the reinforced concrete columns indicates the relative amount of corrosion that had occurred by the end of the exposure period. The horizontal axes indicate the cover thickness and the water/cement ratio, which is used as an indication of concrete quality. The value shown confirms the beneficial effect of increasing the cover and/or the concrete quality. The effect of the nature of the cover in the following three different cases needs to be considered [53]

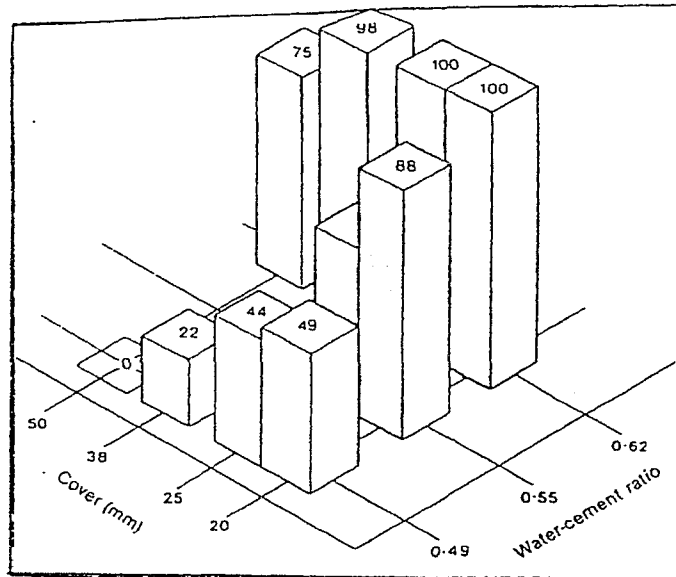


Fig.4.7 Relative corrosion versus cover and water/cement ratio [6]

(i) Uncracked concrete cover: Here the diffusion rates and electrical resistance are controlled by the pore structure, the chemical characteristics of the concrete, and degree of saturation of the pores.

(ii) Cracked concrete cover: Here the width and shape of the cracks become more important factors, and these control the rate of entry of chloride ions or the local rate of carbonation.

(iii) Improperly compacted concrete cover: Here the influence of cavities in the concrete and especially around the steel itself may dominate the entry of chloride and carbon dioxide (CO_2).

Figure 4.8 shows the combined effect of the cover against the number of daily applications of salt before the chloride content reaches the critical value (0.20 percent acid-soluble) and water/cement ratio.

Diffusion into concrete or any substance takes place only when the 'activity' of the dissolved ions or gas molecules in the external environment is greater than the activity of these species in the pores of the concrete

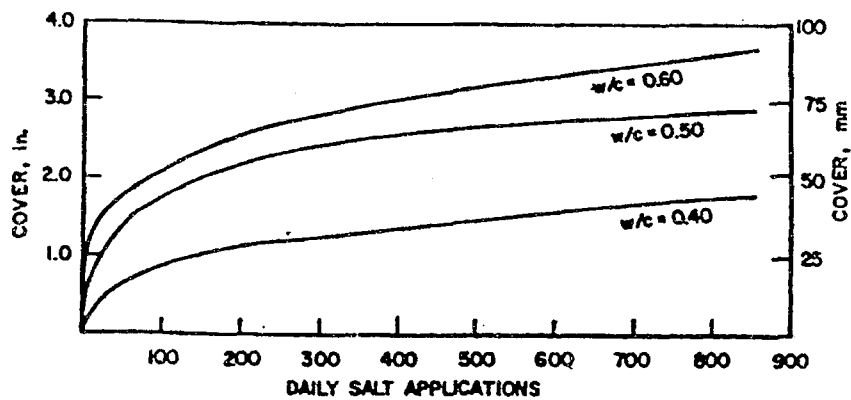


Fig.4.8 Effect of water-cement ratio and depth of cover on relative time of corrosion [32]

. It is this difference in activity that provides the driving force for the diffusion. Activity, in physical-chemical terms, is a parameter related primarily to concentration. Thus, the driving force for the diffusion is the difference in concentration of the species outside of concrete and that within the pores. Diffusion is usually described by Fick's Law [57]:

$$dc/dt = D (d^2 c / d^2 x) \quad (4 - 1)$$

where c is the concentration of diffusing substance at a distance x from the surface at time t , and D is the diffusion coefficient of the process in units of m^2/s . Diffusion coefficient is not a constant, but depends on the temperature, the nature of the diffusing substance, and the nature of material through which diffusion is occurring.

4.4 Construction, Isolation and Construction Joints

There are various types of joints, which are inserted in structures for a number of reasons, such as for construction, control, and isolation joints. Construction or control joints are provided usually to permit limited shortening of portions of the structure. Isolation joints are provided to reduce forces associated with any volume change. Providing isolation joints can reduce cracking that might occur if they are not present; otherwise greater forces are allowed to build up and cause cracks. Construction joints are provided to allow for concrete placement to begin and terminate at certain locations.

These joints introduce discontinuities in bridge decks and parking structures that interrupt the monolithic nature of the concrete surface. Because it is desirable to maintain a watertight surface, frequently these joints are provided with seal element that provide the fundamental resistance to water penetration from the top of the driving surface at the joint [4].

Several approaches have been developed in an attempt to make commonly used structural system more watertight. With some structural systems, such as simple span floor systems, rotation and displacement at supports can be anticipated. The construction can be made more watertight by providing sealed joints at these locations.

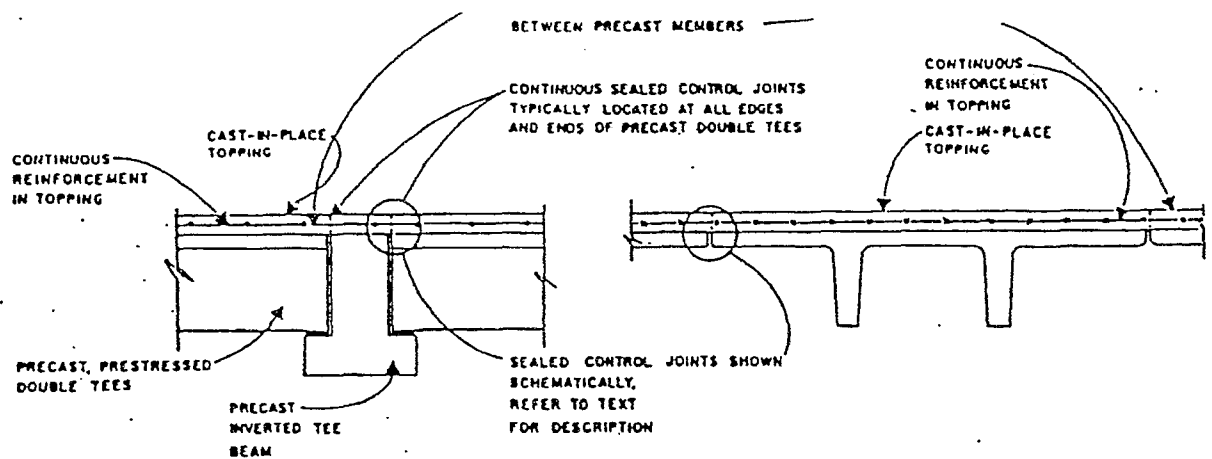


Fig.4.9 Location of some sealed control (construction) joints in topped precast prestressed double-tee parking structure.

Sealed control joints located continuously along the ends of double tees as shown in Figure 4.9 have been used in many parking structures using precast, prestressed double tee construction with a cast-in-place reinforced concrete topping; with this type of construction, cracks also tend to occur in the topping near or along the edges of double tees where the flanges meet.

Sealed control joints located as shown in Figure 4.9 have been used above the flange-to-flange connections in many parking structures of this type of construction.

Sealed joints located as shown in Figure 4.9 have performed moderately well in preventing water leakage through the concrete topping when cracks occur in the joints and movement is restrained by appropriate reinforcement in the topping and connections between the abutting underlying precast members. When water penetrates through the topping concrete or seal, corrosion of embedded reinforcing, other metals, or connection can occur [4].

For other structural systems, consideration should be given to controlling cracks with joints at likely locations of concentrated cracking or movement. The type and location of joints and detailing of their seals are unique to each project and deserve special consideration in construction using precast concrete floor system elements.

Construction joints are often sources of leakage through slabs in parking structures. If deicers are allowed to penetrate through these joints, they may lead to corrosion of the reinforcement or other embedded metals. In the case of unbonded post tensioning tendons, this has been observed to lead to corrosion of the tendon and anchorage hardware in a zone where forces are transferred between the tendon, anchorage, and concrete [35,36,4]. Construction joints required for intermediate stressing anchorage introduce further areas subjected to possible corrosion.

The surfaces of joints which either do not have laitance removed by sandblasting or include other abrasive methods prior to the second casting will have an increased tendency to allow moisture penetration compared to cases where laitance is removed and/or more positive bonding at the joint is provided. Figure 4.10 shows a construction joint provided with a sealed groove to reduce water penetration. Joint fillers, which absorb or retain moisture at construction and isolation joints, have been observed to accelerate the corrosion of adjacent steel. Scaling due to cyclic freezing and thawing may also increase. This is associated with the constant supply of retained moisture at absorptive filler when the sealant has failed [4].

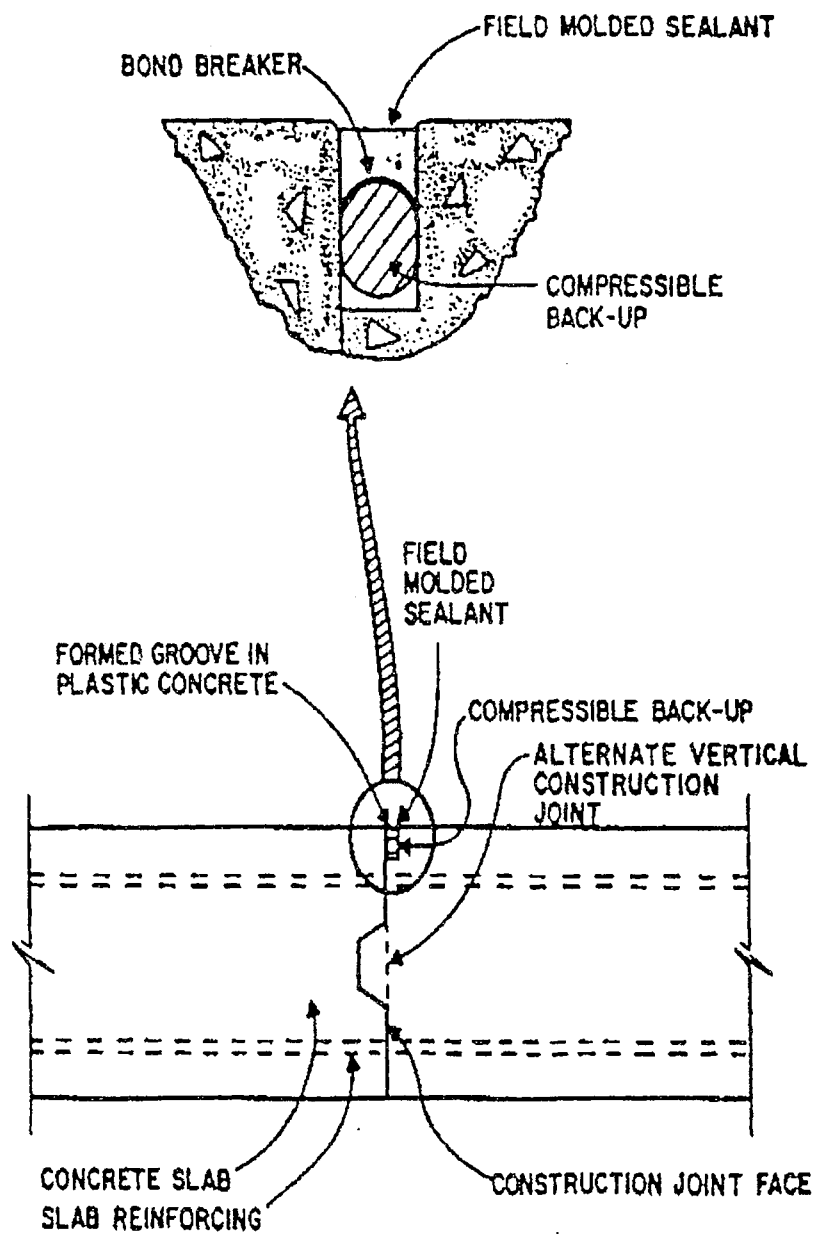


Fig.4.10 Sealed Construction joint

5. STRUCTURAL REPAIR AND PROTECTION MEASURES

5.1 General

The first step in the process of repair and rehabilitation is the assessment of the structure to evaluate the following:

Causes of corrosion of steel;

The extent of damage;

The expected progress of damage; and

The influence of damage on the structural safety of structure, and on its serviceability

On the basis of the initial assessment, the optimal strategy for repair and rehabilitation should be chosen. The strategy adopted should also take into account economic aspects, which include not only the cost of the repairs, but also the overall state of the structure and the additional time period it is expected to serve. Four strategies can be generally considered:

- (1) Replacement or reconstruction of the damaged components.
- (2) Extensive repair to restore the integrity of the damaged components and prevent additional corrosion.
- (3) Local repairs at regular intervals, and continuous monitoring of the development of damage.
- (4) Provision of an alternative supporting structural system.

The first objective of repair and protection of existing concrete bridge decks and parking structures, among other types of reinforced concrete structures, is the restoration of structural integrity. The second objective is to restore the functional integrity in the most effective way [53]. The cause of steel corrosion must be first

identified. Corrosion can be stopped by preventing water, oxygen, and most importantly, chlorides from entering the concrete. Several measures are available to arrest, control, or minimize corrosion, which can be taken either singly or in combination [37].

The repair options of corrosion of the reinforcement embedded in concrete is usually carried out and directed toward one or more of the following attempts:

1. Sealing the concrete surface from the corrosive environment (moisture/water, oxygen, and chloride salts).
2. Controlling and modifying the ambient environment to provide protection.
3. Controlling the potential of steel to reduce the current flow and thereby the rate of corrosion.

Providing a membrane and sealers on the repaired concrete surface to limit the moisture content of the concrete and membrane and sealers will produce an impermeable barrier between the concrete surface and a corrosive environment. Various coating systems have been used. The most common of these is linseed oil and epoxy resins [26]. In Ontario, laboratory and field investigation of the use of linseed concrete started in 1965, and it was found that air entrained concrete was not different in durability from concrete treated with linseed oil. Presently emphasis is placed upon the use of properly air entrained concrete [26].

The impermeable barrier may be a protective coating on the concrete surface, or an elastomeric membrane, or an integral part of the concrete matrix as polymer impregnation, or it may be an overlay of special concrete or internally sealed concrete [1].

Controlling and modifying the environment to reduce corrosion could be achieved by avoiding contamination of concrete with chlorides and by providing a good drainage system to avoid saturation with water.

Cathodic protection is the method used to control the direction of electron flow by providing highly negative steel potentials required for immunity [1].

Not all of the above methods are to be applied simultaneously. The choice of the combination of treatments to be used, the material to be used, and the application methods depend on a variety of factors. Most important are the causes of damage and the extent of the damage. An important guideline is that the repair system should restore the passivation of the steel that was disrupted either by carbonation or chloride [53].

5.2 Patching of Concrete Surface

The concrete around the corroded steel bar should be removed to a depth of at least 50mm beyond the corroded portion. The bar should be exposed around all the circumference of the corroded zone, with clearance underneath the bar being at least 20mm. Light chipping hammers are used to remove damaged and unsound concrete. The exposed reinforcing bars are cleaned, replaced or re-anchored to sound concrete. Prior to patch placement, the patch edges are saw cut to near vertical as shown in Figure 5.1.

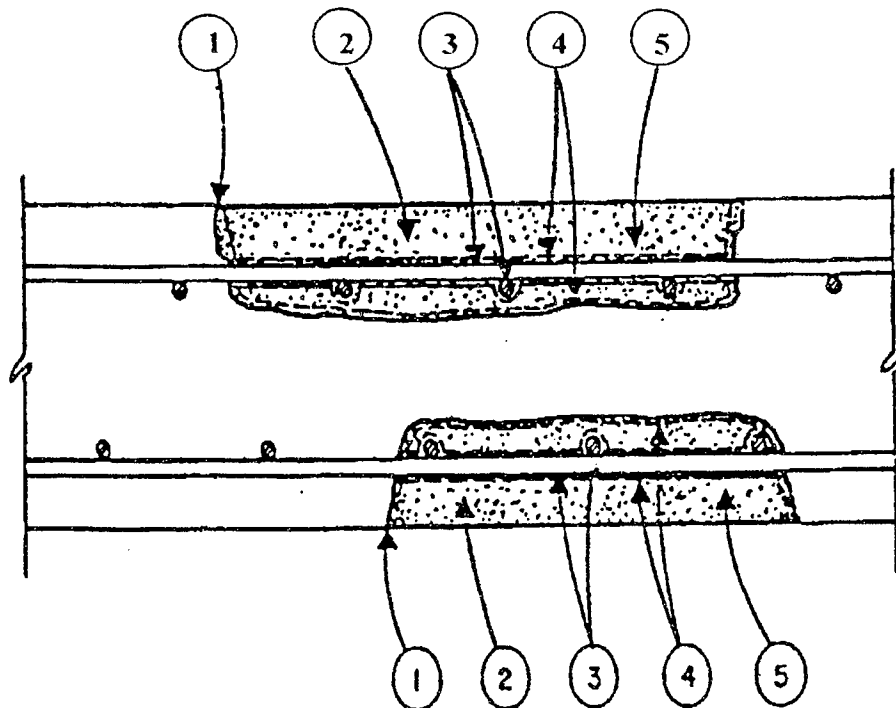


Fig. 5.1 Concrete removal and replacement at patches
(deformed reinforcing bars only, numbers show sequence)

1. Saw cut or chip vertical patch edge
2. Remove all unsound concrete
3. Clean reinforcing steel to bare metal
4. Apply cementitious bonding grout or epoxy coat reinforcing and apply epoxy bonding agent
5. Place, finish and cure patch material

In the removal of concrete, care should be taken adequately to prepare the boundaries of the patch, to prevent feathered edge length. The saw cutting should not cause any damage to existing reinforcement. Shoring may be provided during repair to support the repaired slab [4].

The rust should be removed from the corroded steel surface, to allow intimate contact with the repair mortar or concrete so as to achieve repassivation. Grit blasting is the recommended method for this purpose, but there is often a reluctance to use this method because of the environmental problems, such as the dust and noise generated during blasting. High-pressure water jet with sand is also used to clean the corroded reinforcing bars. After the completion of the removal of deteriorated concrete and rust, there is a need to clean the resulting surface from rust. The contractor usually uses an industrial vacuum cleaner with a small hand brush.

There are traditional compositions consisting of cementitious mortar for repair. However, traditional composition consisting of cementitious binder and fine aggregate do not provide adequate performance. There are modern cementitious mortars used for repair, consisting of more sophisticated formulations that often include a combination of cementitious components with polymeric additives.

Epoxy bonding agents and polymer-modified grouts provide stronger bond but they are less relatively used because of their higher cost. The performance of concrete patches depends on many factors such as the extent of deterioration in the areas adjacent

to the patch. It is believed that a new patch promotes more rapid corrosion of steel in the adjacent areas having high chloride content [4].

Cost-effectiveness is the major advantage of the patching method of repair. Other advantages are practicality and durability. The exposed reinforcement may be coated by epoxy before patching.

Because of the disruption of services and the relatively long curing time necessary for concrete patch material, epoxy mortar is frequently substituted for concrete. Different thermal expansion coefficients for epoxy and concrete cause failure near the bond line of the patch with the original concrete. Also, different modulus of elasticity cause differential deformations under sustained load [4].

When rapid temporary repairs are necessary to maintain facility operations, rapid setting materials are used to patch damaged floors. Polymer concrete, magnesium phosphate cement mortars, and recently silica fume have been used as additives to concrete. Silica fume concrete has more rapid setting and a higher electrical resistance [4].

5.3 Bonded Concrete Overlays

Bonded concrete overlays are most commonly used to restore concrete bridge decks and parking structures. The overlays applied to the treated substrates should have considerable durability and compatibility with the substrates. Durability of the overlays refers to the resistance of both the overlay and substrate treatments to corrosive environments [39].

The new wearing surface will be less permeable to moisture and chloride penetration. The thickness of concrete cover over the reinforcement will be increased, resulting in more protection against corrosion. There are three materials that are most frequently used as concrete overlay, namely latex modified; low slump, high density; and superplasticized low water/cement ratio concretes [4].

5.3.1 Latex-Modified Concrete Overlays

The use of polymer latex, either in the form of a liquid suspension or dry powder premixed in the mortar, is common. Polymer latex used in cementitious mortar imparts improved characteristics over conventional mortar including:

Improved ductility and flexural strength;

Reduced permeability, but retaining the ability for vapors movement to take place in the set mortar; Improved bond to the substrate; and Improved workability.

The polymer latex chosen for such formulations should be compatible with the cementitious matrix, so that the polymeric phase in the form of a film formed during curing will be stable in the alkaline matrix. Also, the content of air that is entrained by the surface-active agents in the latex should not be excessive [ASTM C 1059 – 91]. The favorable bonding and durability properties of latex-modified concrete have made it the major material used in overlays. Polymeric latex is a colloidal dispersion of plastic particles in water. Latex-modified concrete consists of the same ingredients as conventional concrete with the additions of about 1 to 4 percent by weight of concrete [26].

The use of latex-modified concrete follows relatively conventional methods and procedures except for its finishing and curing characteristics. For the best results and properties of latex-modified concrete, the wet curing period to hydrate portland cement should be followed by a drying period to allow the latex particles to form a film.

Testing and investigation by researchers have shown that latex-modified overlays are effective in retarding the ingress of chlorides and preventing chlorides from penetrating the underlying concrete, provided the thickness of the overlay is at least 19mm [26].

The required thickness of overlay determines whether latex-modified mortar or concrete is to be used. Mortar overlay is used when the thickness is usually 25mm or less. Concrete overlays are used for thickness greater than 25mm with a maximum size

of aggregate of 13mm. Typical water/cement ratio of 0.35 to 0.40 and air-entrainment content of not more than 6.5% are usually called for [28].

Self-contained mobile continuous mixers are used on the job site to prepare the latex-modified mortar or concrete. Latex-modified slurry is applied first immediately ahead of the paving process to provide a strong bond coat. The same procedures as for placing and finishing conventional concrete are followed with the overlay. The durability of finished overlay depends on the curing process to a great extent. Wet burlap should be used to cover the surface as soon as the overlay can support it for a period of 24 hours. After that wet curing, air curing follows for 72 hours before opening the facility to service [26].

The high material cost and the tendency of the overlay to exhibit shrinkage cracking are the main disadvantages of the system. Most of the construction problems are results of unsatisfactory finishing or delayed curing [4].

5.3.2 Low Slump, High Density Concrete

The State of Iowa has led the way in the use of low slump, high density concrete. For this reason the system is usually referred to as the Iowa system. The first step is to remove all unsound concrete in a scarifying operation, by which a depth of 6mm to 20mm of the entire existing concrete surface is removed. The scarifying operation is intended to remove most contaminants such as oil drips and chloride salts. After removing deteriorated concrete, the exposed concrete surface and steel bars are sandblasted and a stiff mortar grout is applied to the dry concrete surface. Then low slump concrete overlay is placed and moist cured. High quality control is essential for the success of the system. Cement paste or mortar slurry is usually used to bond the overlay with the exposed surface. Concrete must be mixed on the job site with a slump of less than 25mm. The impermeability and resistance of the concrete to the ingress of moisture and chlorides depend to a large extent on an adequate vibrating and compacting operation. Air entrainment and cement factors of 488 kg/m³ are required by the Iowa specifications [26].

A detailed study to evaluate the system was performed and showed that the low-slump concrete overlays exhibited good durability and retarded the penetration of chloride salts in a satisfactory manner [26].

5.3.3 Epoxy and Polymer Mortars

Epoxy mortars have been used commercially in many repair work applications. The epoxy consists of two liquid components. When the two parts are mixed together, the components react with a strong chemical bond to form the hardened epoxy. Mineral filler is usually used with the epoxy binder to reduce the cost and improve physical and mechanical properties. The coefficient of thermal expansion of an epoxy mortar could be five times greater than that of plain concrete [26]. The main advantage of epoxy mortar is its very high compressive and tensile strengths with excellent adhesion to a wide range of materials. Other advantages include dimensional stability, high resistance to chemical attack, and good electrical insulation [5]. Epoxy concrete overlay may crack due to lack of flexibility, especially in low temperatures. Epoxy mortars have modulus of elasticity higher than that of concrete, which results in different deformation under the same stress on overlays. This will create cracks and permit the ingress of water and chlorides into the underlying concrete [14]. Because of the above mentioned disadvantages and the high cost of material and application of epoxies, its use is limited now to patching operations.

5.4 Sealing Concrete Surface from Corrosive Environment

5.4.1 Waterproofing Systems

Sealing membranes is essential when it is not possible to repassivate the concrete (when the contaminating chloride cannot be completely removed); when the depth of cover is so small (and cannot be increased) that there is a risk of carbonation; or when penetration of chlorides to the steel level within a relatively short period may be expected, even if high quality repair mortar or concrete is used.

The protective coatings have been applied to prevent the ingress of deleterious materials such as moisture and chloride ions. Concrete surface sealers have won wide

acceptance with satisfactory results in North America in general. Waterproofing membrane is most commonly provided by glass fiber in coal tar pitch emulsion. A simplified sketch of the reinforced system is shown in Fig 5.2 [8]. The distinction between the waterproofing barriers is between the liquid applied in place and performed sheet system [26]. The waterproofing system usually requires a durable wearing course to resist cracking and traffic wear and snowplow damage. An asphalt protective wearing surface overlay is generally used, but unfortunately the asphalt is permeable and porous and will allow the ingress of salt-laden moisture through to the membrane surface. Furthermore, corrosion and deterioration of the concrete cannot be detected in the early stages [26].

The major difficulty in the waterproofing system that affects its efficiency and performance is blistering. The trapped vapor pressure under the waterproofing membrane will tend to separate it from the substrate and form blisters. This increase in vapor pressure is a response to environmental change in temperature and atmospheric pressure [26].

Rubberized mastic asphalt with the asphalt emulsion-coated glass fiber systems were identified as the most satisfactory in Ontario though their performance is doubtful. Watertight installation is difficult to achieve and the material requirements cannot be met in one product. Resistivity measurements of waterproofed concrete slabs show also decreased electrical resistivity, which is a direct indication of expected corrosion [26].

5.4.2 Internally Sealed Concrete

The principle component of internally sealed concrete is the use of fusible polymeric substance in the concrete mix, and followed by application of heat to the hardened concrete after curing. The pores of concrete are filled and effectively sealed against the penetration of salt-laden moisture [26].

A 25/75 blend of montan and paraffin wax added to concrete mix at a dosage of 3 percent by weight showed satisfactory results and proved significant reduction in

water and chloride ingress into the concrete. The wax is melted and distributed in the concrete by maintaining a temperature of 100° C at the surface [26].

The internally sealed concrete was found to have excellent durability, but its strength is slightly reduced when used with air-entrained concrete [26]. The author's opinion is that the use of air entrainment in concrete is necessary for the advantageous properties of both plastic and hardened concrete as described in Section 4; however, the monton /wax is not commercially available and the method is not applied in practice.

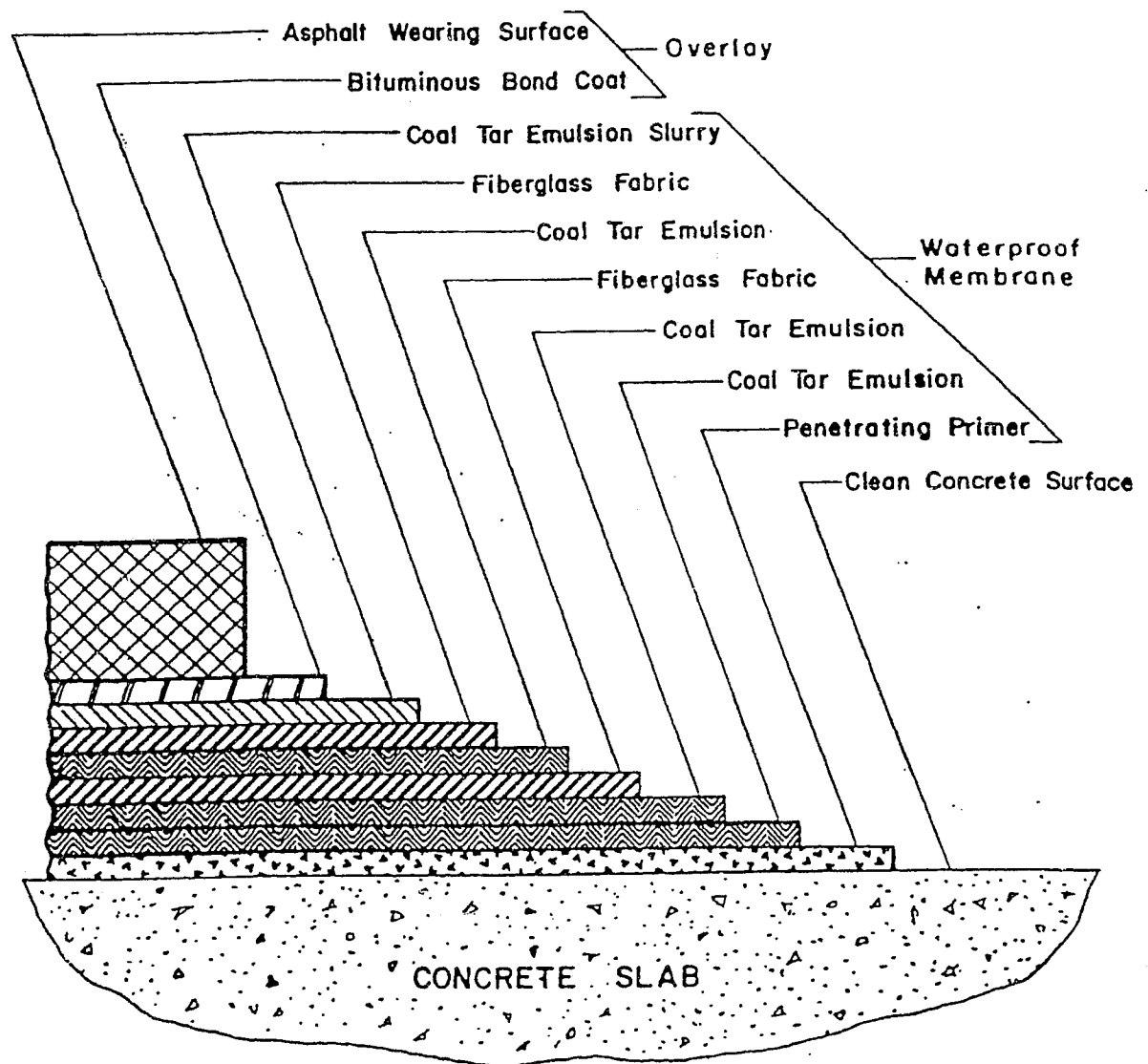


Fig. 5.2 Typical Bridge deck protective system [8]

5.5 Principles and Development of Cathodic Protection

5.5.1 General

Corrosion of reinforcing steel in concrete is a widespread and enormously costly problem in many parts of the world including the United State and Canada. Numerous concrete structures including bridge decks and substructures, parking garages, balconies and others are deteriorating as a result of reinforcing steel corrosion. Virtually any reinforced concrete structure is susceptible to the ravages of corrosion if subjected to the right environment [58].

Visual signs of corrosion-induced damage on many types of reinforced concrete structure are becoming more and more prevalent. In many parts of the country, one can hardly drive across the bridge or enter a parking garage that does not have some degree of corrosion damage. The rate of concrete deterioration at any given time is dependent on many factors including the corrosion rate, reinforcing steel concentration, concrete properties, cover and the environment. Once corrosion has begun, there is one thing for certain – it will only get worse and it will do so at an ever-increasing rate. Ultimately, if corrosion is allowed to continue, structural integrity can be compromised due to loss of a section of the reinforcing steel and/or loss of bond between the steel and the concrete, and replacement may be the only solution [57].

In order to mitigate or control corrosion problem (provide low future maintenance and long-term protection), specific information is needed for any given structure. Fortunately, proven technology and scientific methods are available to evaluate corrosion of reinforcing steel (and other embedded metals) and associated damage in reinforced concrete structures. It is only after this information is obtained through a detailed corrosion condition evaluation that a suitable repair and protection specification can be developed for a corroded structure. It is important to point out that concrete itself can deteriorate regardless of the condition of embedded reinforcement. Examples of these include freeze-thaw damage and alkali-silica reactions. Therefore various concrete tests are required in conducting an overall evaluation.

5.5.2 Cathodic Protection

Cathodic protection (CP) is widely used, and it is an effective method of corrosion control. Many people, including engineers, believe CP is so complicated and expensive that it has no practical use in the concrete rehabilitation industry. Then there are those who say CP doesn't work or that it is unreliable in the long term. In fact, cathodic protection is one of the most effective and available methods for the long-term protection of actively corroding concrete bridge decks and parking structures. While most of the remedial measures work by preventing or retarding the ingress of moisture, oxygen and chloride to the level of reinforcement, the cathodic protection method prevents corrosion in the presence of salt, oxygen and water, regardless of pH.

The principle of cathodic protection is well understood and proven to be effective in arresting reinforcing steel corrosion on approximately fifty bridge decks and several parking structures in Canada and in the United States; fifteen of those are in Ontario alone [40]. Some of the application details are still in the development stages and practical problems being currently encountered deal with criteria of protection, design and monitoring the system performance. However, work is continuing to develop this efficient method for cost-effective application procedures and to achieve full understanding of the determinable effects on concrete, steel, and particularly on concrete/steel bond [41].

Besides stopping reinforcement corrosion, the other advantage of the cathodic protection method is that its performance can be monitored by non-destructive test methods [26]. Some researchers [42] believe that as a result of the application of the cathodic protection method, negative chloride ions are drawn away from the vicinity of reinforcement to the anode, where they are oxidized to form chlorine gas; thus the reinforcement restores its passivating oxide layer due to the reverted alkaline state of the surrounding concrete. However, the cathodic protection system may be applied only to decks in which the concrete is sound and properly air entrained. Appropriate structural repairs should be performed before installing the system on deteriorated concrete slabs [4, 26]. After millions of dollars of expenditure on research in the area of corrosion and its mitigation, cathodic protection evolved as the only technique that

could positively arrest corrosion of steel in the existing concrete structure. In fact, some time ago the Federal Highway Administration (FHWA) acknowledged that cathodic protection is the only technique that had proven to stop corrosion in salt-contaminated bridge decks regardless of the chloride content in the concrete [59].

5.5.2.1 Principles of Cathodic Protection

The mechanism of the electrochemical corrosion process of reinforcing steel in chloride-contaminated concrete is discussed in Chapter 3 of this report.

Figures 5.3 (a), (b) and (c) show the corrosion reactions in a typical chloride contaminated concrete deck. In Figure 5.3 (a), the top rebar mat is most commonly anodic because of chloride ion penetration and its higher concentration near the top of the concrete cover area. The bottom mat is cathodic, and a difference in electric current will flow between the connected top and bottom re bars with a flow of negative ions through the concrete, which serves as an electrolyte. In Figure 5.3 (C), the anodic corrosion reactions (production of electrons) at the top of the mat, and the cathodic reactions at bottom are shown with the ionic transfer through the saturated concrete deck [42]. It should be noted that the same reactions, cathodic and anodic, could take place in micro-galvanic cells along the surface of one rebar.

The protection at both the cathodic and the anode, shown by equations (3-1) and (3-2) is reversible. Supplying sufficient current in the proper direction causes the current discharging anodes to become current receiving cathodes, and F^{++} ions will be retained to Feo as shown [15, 42].



In order to achieve the cathodic protection requirement that all the existing anodes on the steel receive current, the half-cell potential of all the steel must have less potential (more negative) than the most negative of the anodes

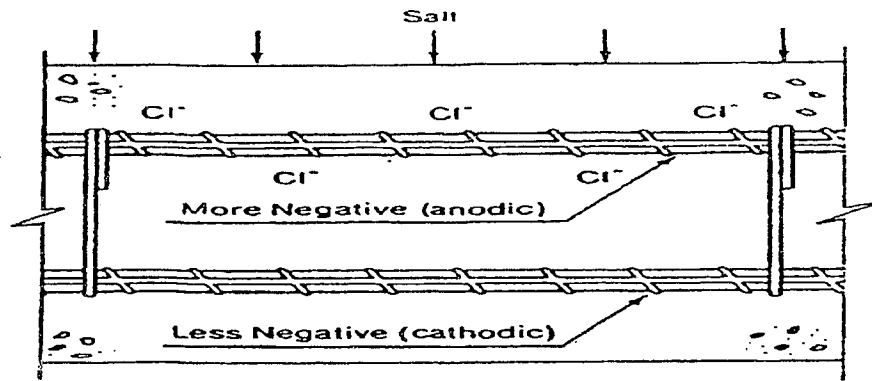


Fig. 5.3(a) The corrosion mechanism potential difference [42]

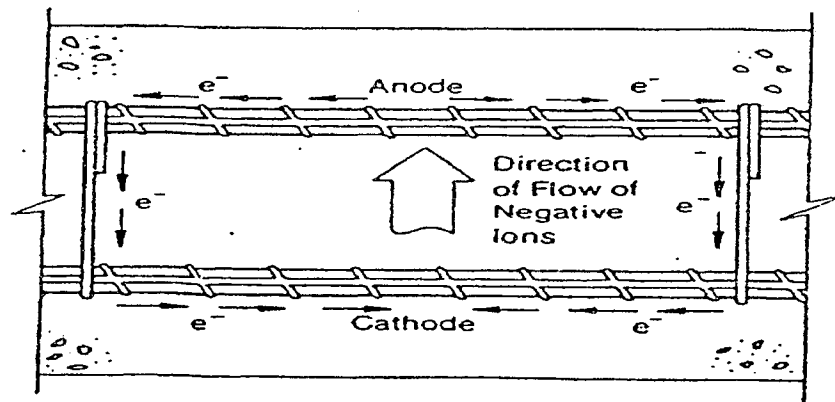


Fig. 5.3(b) The corrosion mechanism current flow [42]

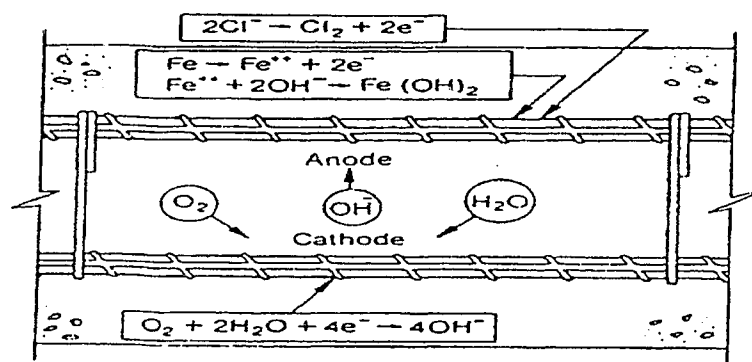


Fig. 5.3(c) The corrosion mechanism typical reaction [42]

There are two methods by which cathodic protection can be applied to concrete reinforcement, namely the galvanic or sacrificial anode and impressed current method.

5.5.2.2 Galvanic or Sacrificial Anode

In this method, CP is based on the principles of dissimilar metal corrosion and the relative position of specific metal in galvanic series. No external power is needed with this type of system and much less maintenance is required. Such a system also provides protective current primarily to areas on the steel surface, where it is most needed. The concrete reinforcement is electrically connected to a metal or alloy more negative, or higher in the electromotive series, than the reinforcing steel to be protected. Magnesium, zinc, and aluminum are the most suitable anodes that can be coupled for the protection of steel in concrete. The natural potential difference between the steel and the sacrificed anode is the current driving potential. The electrons move from the anode to the cathode, thus providing the negative charge to steel. The sacrificial anode, zinc, for example, corrodes, sending a positive charge to the electrolyte in the form of zinc ions, Zn^{++} [1, 26, 42]. Galvanizing the steel by applying a thin surface film of zinc is, in fact, only a form of this method of cathodic protection [59].

However, the relatively high resistivity of the concrete led to early opinions that the low driving voltage provided by such systems would be inadequate for CP of steel in concrete. Other disadvantages are the rapid consumption of the sacrificial anode and the need for replacement, and the controlled nature of the galvanic system after installation [59].

5.5.2.3 The Impressed Current System

The impressed current cathodic protection is achieved by driving low voltage direct current from relatively inert anode material through the concrete to the reinforcing steel. Direct current of sufficient magnitude and direction is applied, so as to oppose the natural flow of current resulting from the electrochemical corrosion process. The direct current is supplied by an external power source, most often a CP rectifier. Recently, solar power has received attention and research is under way. The cost of

power is virtually negligible, but the cost of installing a meter exceeds the cost of the power. The required power is as low as 0.22 watts per square meter of concrete surface or less [59]. The anode materials are usually selected on the basis of durability and conductivity since they do not depend on the relative potentials of anode and steel. High silicon cast iron and carbon are commonly used [26]. The mechanism of the impressed current cathodic protection system is illustrated in Fig. 5.4 (a) and (b).

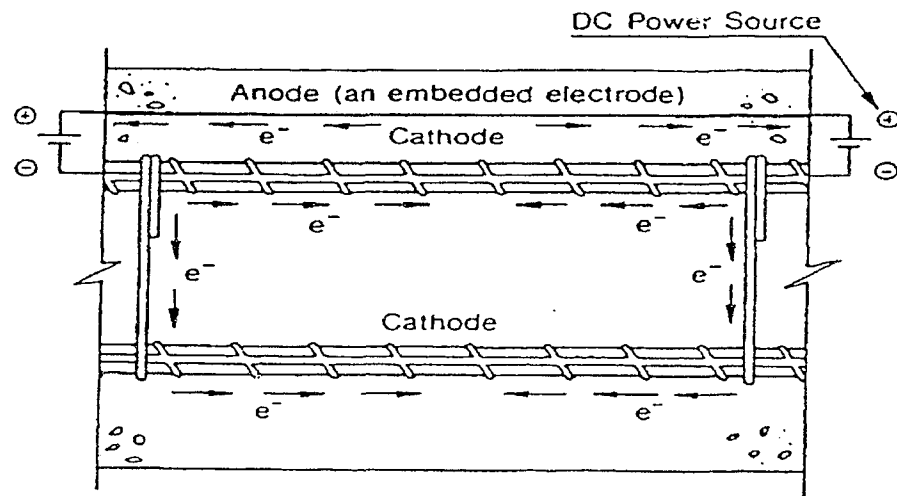


Fig. 5.4 (a) Cathodic protection current flow [42]

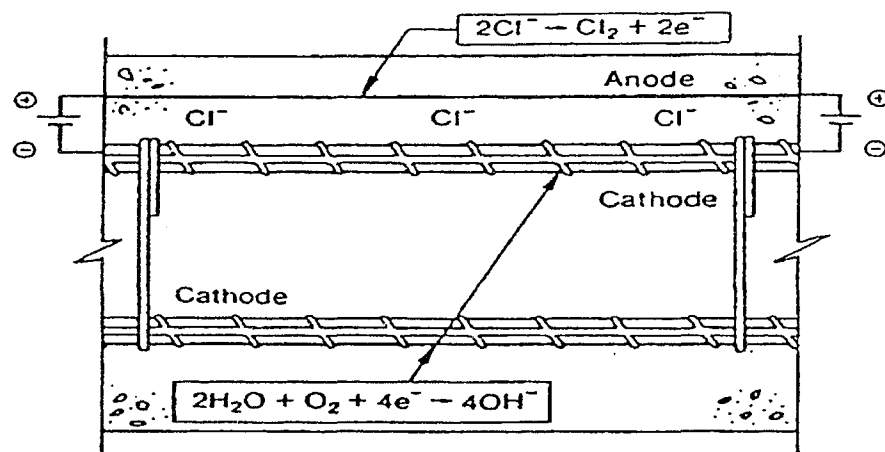


Fig. 5.4 (b) Cathodic protection typical reaction [42]

5.5.3 Half Cells

Electrical potential measurements are made in order to determine and evaluate the effect of the cathodic protection on corrosion of steel. Usually a copper electrode in saturated copper sulfate solution half-cells (CSE half-cell) is used to take measurements. The copper sulfate solution will be in contact with the concrete and the copper electrode is connected to the steel through a high resistance voltmeter. The measured electrical potential is essentially an indication of corrosive tendency of the steel in the concrete environment relative to the corrosive tendency of the copper in its environment.

The rectifier is provided with circuitry to continuously compare the voltmeter to predetermined criteria and to adjust the current supply to the system as requirements vary [41].

5.5.4 Potential Criteria

It was shown earlier that the corrosion rate of steel in concrete is controlled by oxygen availability. In the cathodic protection system, polarization of steel is controlled by the applied potential value [1]. Analytic procedures show that there should be a critical protective current flow through the cathodic protection circuit below which protection is not sufficient and above which the steel/concrete bond may be damaged [59]. Theoretical studies have shown that the optimum protective potential for steel in concrete depends on the chloride concentration [44].

The required criteria for cathodically protected steel embedded in concrete are not clearly defined, and it appears that a single best criterion has not been agreed upon yet [59]. Most commonly, a potential value of -0.85V measured to standard copper-copper sulfate half-cell (SCE) is adapted as the measure of the optimum level of cathodic protection of steel in concrete [41].

5.5.5 System Connection and Current Distribution

A reinforced concrete deck reinforcing steel consists generally of a top and bottom mat. The upper reinforcement is usually susceptible to the penetration of deleterious materials and consequently corrosion. Theoretically, each rebar in the top mat to be protected must be connected to the negative terminal of a DC rectifier. This is not practically feasible, and it is assumed that electrical continuity is provided by bar contact point and tie wires. The top and bottom reinforcing mats and the structural steel are normally connected by tie wires and/or chairs [43]. Electrically isolated bars will receive little or no current and will be affected by the cathodic protection circuit current and can be corroded by stray current. It should be noted that such isolated elements will corrode faster than before the application of the cathodic protection system due to localized corrosion at the point of current exit from the rebar [41].

There are two systems to connect the positive terminal of the rectifier to the electrolyte (the concrete), the conductive overlay and the wire or linear anode system. The conductive overlay method was the first and the most commonly used in cathodic protection systems in concrete decks. The conductive overlay system consists of a cast silicon iron alloy embedded in conductive coke breeze asphalt layer and covered by conventional asphalt concrete wearing course [43] (see Fig. 5.5). The use of conductive overlay is associated with durability and structural problems as discussed in this section earlier. The wire anode system uses long electrodes of platinized niobium copper core wire strands as the anode. The strands are placed into slots cut in the concrete. In both the conductive overlay and wire or linear anode current distribution system, the conductive layer (the anode) must be kept isolated from the reinforcement otherwise the system will be short circuited [43].

5.5.6 Problems with System Performance and Maintenance

In general, the evaluation measures have indicated that the application of cathodic protection system to new and existing concrete bridge decks and parking structures has been performing satisfactorily. However, one of the major problems of current installations is durability of the conductive overlay.

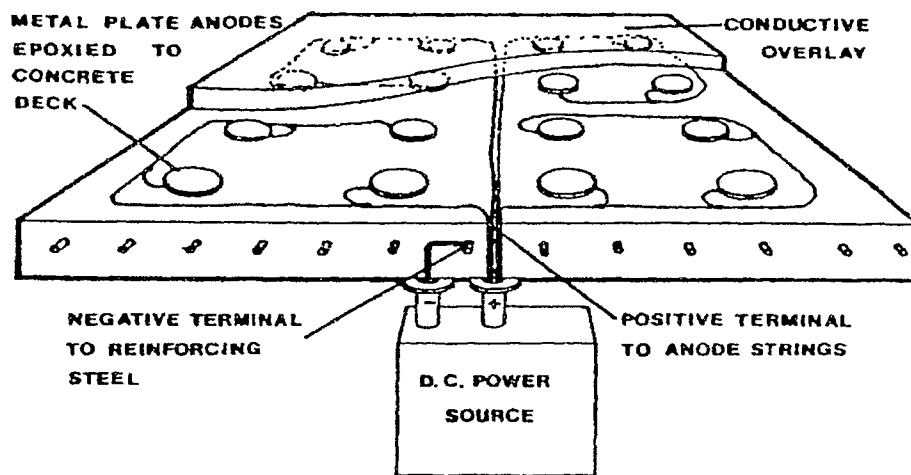


Fig.5.5 Simplified drawing of a conductive overlay cathodic protection system using “pancake” type in series strings of 4 anodes each [41]

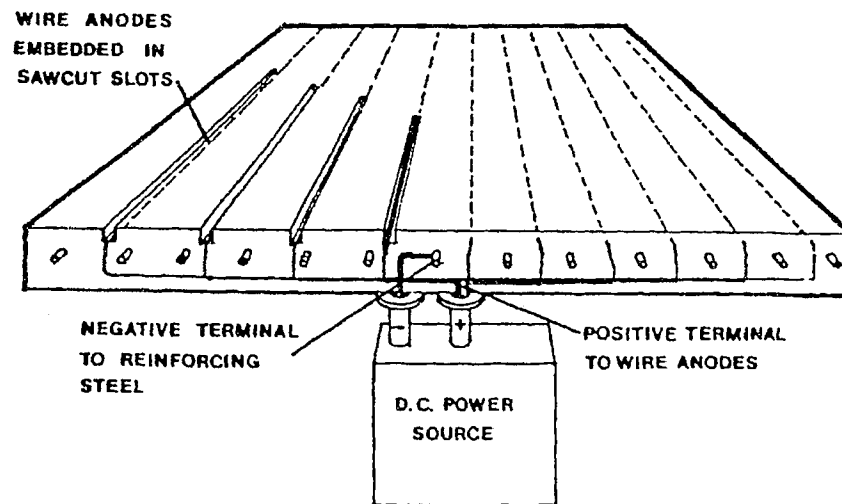


Fig. 5.6 Simplified drawing of a “linear” or “distributed anode” cathodic protection system, showing the anode wires embedded in slots saw cut into the concrete [41]

The structural behavior of conductive overlay is in general inferior to the standard paving materials and the layer has to be replaced periodically because of the lack of stability under traffic loads and its additional load [43]. The installation of overlay increases the probability of trapping and holding moisture against the concrete surface. This will be favorable to the cathodic protection system since it will improve conductivity, but on the other hand, it can lead to severe freeze-thaw damage to the concrete in winter conditions [41].

Application of cathodic protection current under a potential of -1.17 V (SCE) or higher will result in evolution of hydrogen bubbles at the surface as the result of the electrolysis of water. Certain reaction at the cathodic steel surface can result in decrease in bond strength between the steel and concrete [43]. Routine system maintenance can be a problem. Several embedded half-cells for the automatic potential control have failed and some of the electric connections are susceptible to damage [42].

Epoxy - injected decks, as a repair to delaminated areas cannot be cathodically protected because the nonconductive epoxy layers will isolate these areas from receiving the protective current [43].

The cost of cathodic protection system is relatively higher than other repair methods since it is still in the development stage. The cost is expected to decline as improvements are made in application technology, methods, maintenance and installation experience [43].

6. CASE STUDY

6.1 Rehabilitation of 19th Avenue Bridge, Markham, Ontario

Rehabilitation of concrete in bridges prematurely damaged by deterioration continues to be a major problem all over the world. Approximately 564,000 bridges are standing in the United States. At least 105,500 of them need repair or replacement. Millions of square feet of bridge decks show heavy deterioration, cracking, spalling, corrosion of reinforcement, chemical attack, and the like. One such bridge, the 19th Avenue Bridge in Markham, ON, was replaced in 1998. This was a very beautiful, old single-span reinforced concrete bridge, built in 1928 at the mouth of Markham Valley.

According to the Town of Markham records the deck of the bridge was replaced in 1945 due to deterioration. The bridge is situated in a widespread residential sector between Warden Avenue and Kennedy Road on 19th Avenue, and is the only ready transportation route for local people and the surrounding business area. Due to Markham's rapid expansion, road traffic has increased dramatically in the past forty years or so. Since 1995 a number of residential developments have been constructed, and a fair-sized residential sector has emerged.

6.2 The Investigation Process:

The techniques for effectively evaluating the extent of concrete deterioration are numerous and rapidly evolving. Confusion often exists regarding the appropriate number and types of test methods required that provide optimal information for developing suitable restoration strategies. The methods and techniques used during the investigation and evaluation of the condition of the 19th Ave. bridge structure follow.

To implement the investigation, ensure a successful evaluation, and determine cost-effective solutions, the following five fundamental questions should be answered.

1. What is the extent of the deterioration?

2. What caused the defect, damage, or deterioration?
3. Can or should the concrete unit or structure be restored to its original condition?
4. Will the damage occur again to the same degree after rehabilitation?
5. What are the key effects of the development of a rehabilitation strategy?

Repair of damaged or deteriorated structural concrete can be handled by experts -- at the design and development stage, when the type or the extent of the repair and/or protection work must be decided. The typical format that is generally followed for an investigation, design and construction or restoration is shown below.

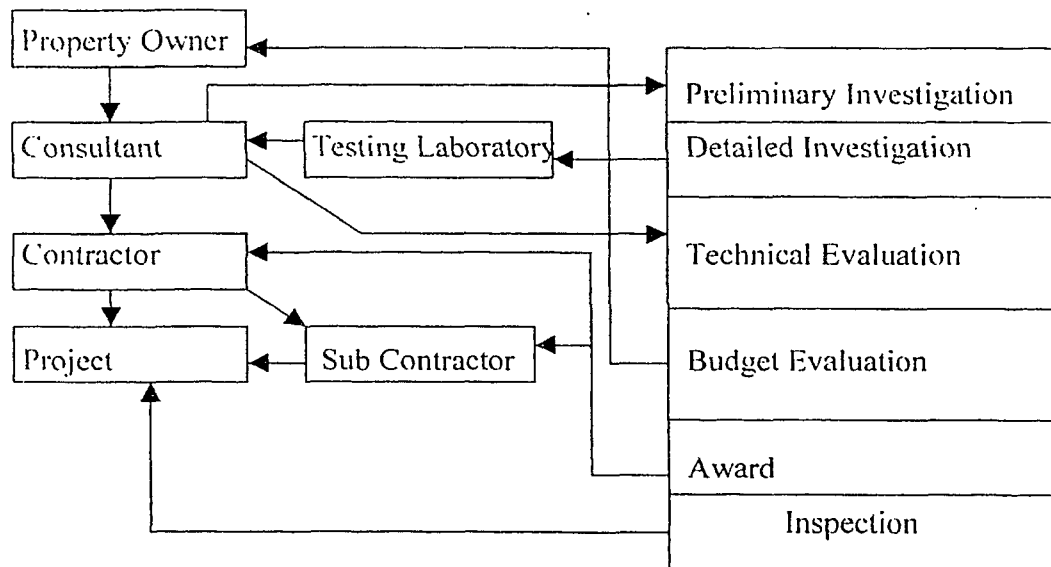


Fig.6.1 Typical Restoration Project Format

6.2.1 Field Inspection:

The first phase of the project included an in-depth inspection to determine the physical condition of the structure. The bridge was visually inspected for spalls, cracks, rust, stains, discoloration, corrosion of reinforcement, and other indications of concrete deterioration. The surface areas were also examined by sounding (hammer tapping) to locate delaminated areas. The inspection result was as follows:

- The top of the slab was deteriorated over almost 65% to 75 % of the area because of the improper slope in the deck for water drainage. In the expansion joint area spalling had occurred, which certainly was one of the major causes of the deterioration.
- Cracking, light in most locations and moderate to heavy at others, was observed throughout the deck surface. Some longitudinal and random cracking was also observed.
- Severe deterioration was found on the underside of the deck slab including the expansion joints. Leakage through the joints had caused extensive corrosion of the reinforcement, spalling and delamination of the concrete cover. The beam soffits were also severely damaged due to the spalling and in many places reinforcement was naked (exposed).
- Cover to reinforcement at the bottom of the deck slab and beams soffit was less than 20 mm: measurement indicated that at some locations the cover did not exceed 7 mm. The corrosion process seemed to begin with no chlorides or with low value of chloride. This occurred because the front of carbonation reached the reinforcement and the concrete alkalinity did not protect the steel from corrosion. Found by the visual inspection, these areas were the most severely deteriorated. The zone along the expansion joints at the underside of the deck had suffered the most damage from corrosion of reinforcing steel. It had also been exposed to repeated cycles of wetting and drying and freezing-thawing, often in saturated conditions.

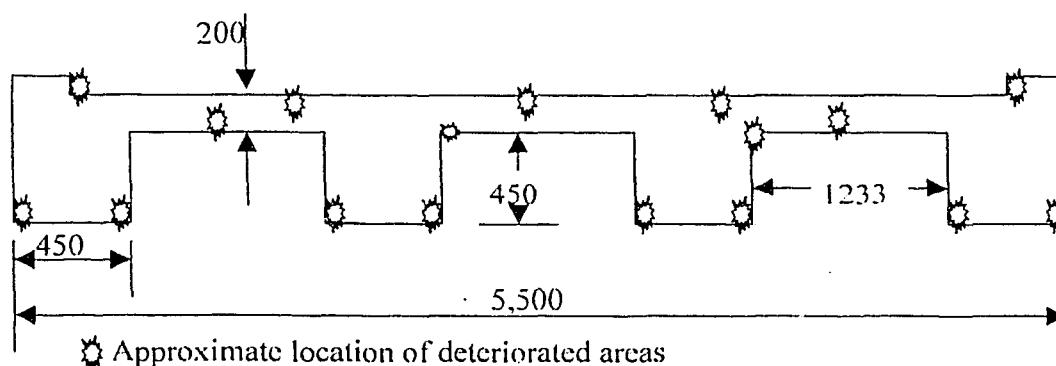


Fig 6.2 Cross-section of Existing Bridge Deck. * (All sizes are in mm)

- The expansion joints were found to be without elastomeric compression seals. The joints, poorly treated with some type of rubber or bituminous material, were in a very deteriorated condition. At slab corners, along the expansion joints, the spalling was more severe because the cracking took place more rapidly due to greater chloride, moisture, and oxygen penetration and build-up from the two surfaces. Also at this location, the resistance to cracking provided by the adjacent concrete for an infinite surface was least at the surface boundary.
- The abutments were in better condition compared to the underside of the deck slab. In some places there were random cracks of different width from 1mm to 2.5mm wide and 25 to 38 mm deep.

6.3 Testing Procedure

A concrete sampling and testing program was carried out to supplement visual observations and to determine the potential durability of the concrete and the expected remaining service life of the structure. The program included obtaining and testing cores and samples for compressive strength, chloride ion content, depth of carbonation, pH value, and for performing petrography examination.

The sampling plan was designed to obtain samples from the concrete areas judged to have light, moderate, and severe deterioration. The most severe areas of concrete deterioration were adjacent to the expansion joints on the underside of the deck slab, beam soffits and in some areas of abutments.

Cores taken near the expansion joints were examined visually and tested for compressive strength. A total of 12 cores were taken from various locations throughout the bridge. Using the dry pulverizing method, 8 samples were taken from six locations of the underside of the deck slab adjacent to expansion joints. The depth of the six shallow cores was up to 75mm. The remaining six samples were taken at a depth of approximately 125mm. For depth of carbonation, test cores 75mm in diameter were

taken at three locations. Two samples of concrete dust (left over from the chloride ion testing) were taken to determine the pH value of the concrete.

6.3.1 Compressive Strength

Compressive strength tests performed on cores taken at the top of the deck areas indicate concrete deterioration; the compressive strength averaged 3000 psi (approximately 20 MPa). The Town of Markham has no record of the original design of the bridge or the replacement of the bridge deck to determine how much compressive strength was lost over time and due to the deterioration effect. Some of the core contained delamination and cracks, and the reinforcement in two cores had corroded up to the extent that the bond between the concrete and steel was severely affected. A few cores were not tested because they contained the reinforcing steel bars or delamination and cracking. Throughout the bridge, black mild steel was used with the bar diameter varying from 13mm to 19mm.

6.3.2 Carbonation

Laboratory measurements of the depth of carbonation using a phenolphthalein indicator showed that color changes occurred at an average depth of 16mm. Testing for pH value indicated an alkalinity of concrete of about 8.5 to 9.0. The petrographic examinations showed that there were no entrained airs and the concrete was of low quality. The spalling may have been caused by freeze-thaw cycle distress, because there was no entrained air in the concrete. The bond of cores and fine aggregates to the cement matrix was not good. The paste was not of dense quality; there might be a few reasons, such as a high water/cement ratio or improper curing.

The cracks on the surface of the concrete were map or pattern cracking, which is usually caused by the alkali-silica reaction. It was very difficult, if not impossible, to determine the existing state of the reaction and to predict the remaining service life of the structure. No correlation was observed between the degree of alkali-silica reactivity, the external deterioration, and the age of the concrete.

In some areas, the cracks were shallow and both parallel and normal to the exterior concrete surface. The cracks penetrated to a depth of about 25mm to 35mm. The paste near the cracks was carbonated. In the interior of the concrete, the affected concrete particles had become soft and internally cracked without the cracks extending into the mortar. Carbonation results in various physical changes, but the main effect is a reduction in the alkalinity of concrete from approximately pH 8.5 to 9.0. This change causes the reinforcing steel to become unprotected from corrosion because of lowering of pH of the concrete. The carbonation usually moves into concrete from exposed surface at a rate that is dependent upon the moisture content of concrete. The carbonation front progresses rapidly when the humidity is between 50 % and 70% and is negligibly slow at both low and very high relative humidities.

6.3.3 Chloride Contents

Sampling and testing for total chloride content was carried out in accordance with AASHTO T-260. The shallow samples showed levels of chlorides that ranged from 0.65 to 6.4 kg/m³ of concrete, and the deep samples of the chloride content ranged from 0.18 to 2.3 kg/ m³.

The total value of the chlorides found at the level of reinforcement in spalled areas was well in excess of critical amounts of chlorides required to create a corrosion problem. High salt concentration resulted from a progressive build-up of chloride levels due to saline water passing through the expansion and construction joints and the capillary movement of saline solutions through the concrete. The amount of chlorides necessary to destroy the passive film on the reinforcing steel is not a single value for all situations. It depends on the value of pH, water and oxygen contents, and the bond between concrete and reinforcing steel. The actual values are not available.

Deicing salts are transmitted with snow and ice to the undersides of vehicles. The salty snow and ice that melts was pounding on the bridge deck due to inadequate drainage and seeping through damaged seals at expansion joints. Reduced concrete cover and some microcracking in the concrete surface permitted moisture, chlorides,

and oxygen to penetrate to the reinforcing steel slowly in uncracked areas and more quickly through cracks.

6.4 Evaluation and Decision Making

Based on all of the above test results, we may note that the concrete is still in good condition structurally, and it remains confined within the reinforcing steel in the majority of areas. Moreover, the probability of structural failure may be minimized by slowing down expansion, requiring immediate rehabilitation measures. The existing structure was a single-lane bridge and was built only to serve local traffic. The Town of Markham had an objective to rehabilitate the existing structure if possible and to increase the bridge width to accommodate two more lanes, one each way. The consultant submitted two proposals to the town:

- 1) To rehabilitate the existing portions of the bridge and add a two-lane structure adjacent to the existing bridge.
- 2) To demolish the existing bridge and build a new bridge, which will be able to accommodate existing traffic and have reserve capacity for the future.

The Town of Markham found itself more comfortable with the first option, because they were very nervous about the disturbance of the natural landscape and with the new price. According to the town regulations, before a decision is made, public opinion must be obtained. The town called a public meeting before they gave their recommendation to the council committee that usually makes the final decision.

The local community had a genuine concern that during the heavy rainy season the water level in the creek goes higher than the deck top, and then nobody can pass the bridge. In the public meeting public delegates, with the help of their local councillors and members of provincial parliament (MPP), succeeded in their demand for the construction of a new bridge. The decision was made, therefore, to construct a new bridge.

6.5 New Structure

6.5.1 Durability Criteria in Bridge Structures

The durability criteria for bridges differ from those of most other structures. According to CSA standard, major bridges are designed to serve for 45 years, but most bridge structures serve more than their design life span. Challenging this longevity are not only the normal physical and chemical attacks on the concrete itself and on the reinforcement, but also the intentional heavy applications of salt to the decks of bridges and, in the case of railroad and floating bridges, the accumulation of internal damage (fatigue) due to cyclic dynamic loading

Great progress has been made recently in identifying causes and finding preventive and mitigating measures aimed at specific phenomena. Advanced laboratory technology and equipment have combined with field observations to describe the processes, prescribe tests for early diagnosis, and develop appropriate countermeasures.

A number of tests of specific parameters have recently been developed and are now being implemented as mandatory criteria for bridges designed for service lives in excess of 45 years. Ever more refined nonlinear, inelastic, finite element analyses are being employed to reveal areas of probable cracking due to structural response. Rigid enforcement of specified quantitative criteria, focused on specific parameters, ignores the interactive complex process involved. Excessive reliance on such criteria impedes rather than helps the constructions progress and may be counterproductive to durability.

What is required instead is a holistic systems approach, looking not only at the individual processes and phenomena, but also at their interaction. *Durability may be defined as the continued ability of the structure to satisfactorily serve under normal operating conditions with minimum maintenance.* Applicable design codes address durability by limiting the water/cement ratio and specifying minimum cover of concrete over the reinforcement. Other clauses specify air entrainment and air void parameters, and properties of the component materials. The codes also address structural

performance in terms of cracking and crack width as being significant measures of durability.

6.5.2 New Structure

The new bridge design was based on the durability principles. Sheet piles were used to isolate the underground concrete footing from water contact, possible seepage or other chemical attack from the soil. The 6mm-thick corrugated sheet piles were driven 2.75m below the bottom of the footing. The sheet piles were embedded in the concrete footing with 25mm-thick dowels welded to the sheet piles and embedded in the footings concrete.

Throughout the bridge epoxy-coated reinforcing steel bar (diameter from 10mm to 25mm) was used to protect the bar from corrosion or other chemical attacks. The most important aspect during the construction phase was to maintain the quality of the concrete, cover of the reinforcement, and workmanship, as shown in Table 1. The assigned inspector by the consultant strictly checked the cover, size and number and type of re bars before allowing the pouring of concrete.

The concrete was supplied by one of the reputable concrete mix suppliers of the area, specified by the Ministry of Transportation of Ontario (MTO). All concrete was prepared strictly according to the MTO design mix. The concrete quality, slump, cylinders casting and time were strictly checked and recorded. The concrete in the deck was poured through pump to maintain the quality and design with proper draining, ensuring that there will be no accumulation of water on the deck top. The deck top was properly screed to maintain the slope and help drain the water. Figure 6.4 and Table 3 shows screed elevation and spans.

The deck was properly waterproofed according to Ontario Provincial standard (OPSD), with hot asphalt rubberized membrane, by a specialized crew. After waterproofing the leakage/seepage tests were performed, in which 100mm-deep water was placed for 48 hours to check for any leakage from the waterproofing system. After

Table 1:Class of Concrete mix and cover

Description	Class of Concrete (Mpa)	Max. Size of aggregate (mm)	Clear Cover (mm)
Footing	35	19	100 +-25
Abut & W. wall	35	19	70 +-25
Deck	35	19	70+-20 top of deck 50+-10 bottom
Barrier Walls	35	19	70 +- 20
Approach Slabs	35	19	70 +- 20

Table 2:Concrete mix design

Material	Proportions kg / m³
Portland cement type I	445
Fine aggregate	830
Coarse aggregate AASHTO M 43 size 7	980
Water	155
Water reducing admixture	3 Liters
Air entraining admixture	0.6 liter
Air content	6.5 +- 1.5%
Total	2,414
Slump	
Deck	20 +- 2.5 cm
All other components	15 +- 2.0 cm
28 days compressive strength	35 Mpa

successful results from the water test, the 90mm-thick asphalt was placed according to specification Figure 6.5. The expansion joints were treated with hot applied asphalt membrane with asphalt-impregnated protection board on the expansion joint side Figure 6.7. On the rigid side dowels were embedded from deck to approach road. In the wing walls and barrier walls the specified slopes and 20mm chamfers were made accurately as specified for water drainage. On the top of the barrier wall, an 89mm-diameter hot dip galvanized steel railing was installed. All construction joints were sealed with 6mm-thick PVC water stops to avoid possible water seepage or leakage.

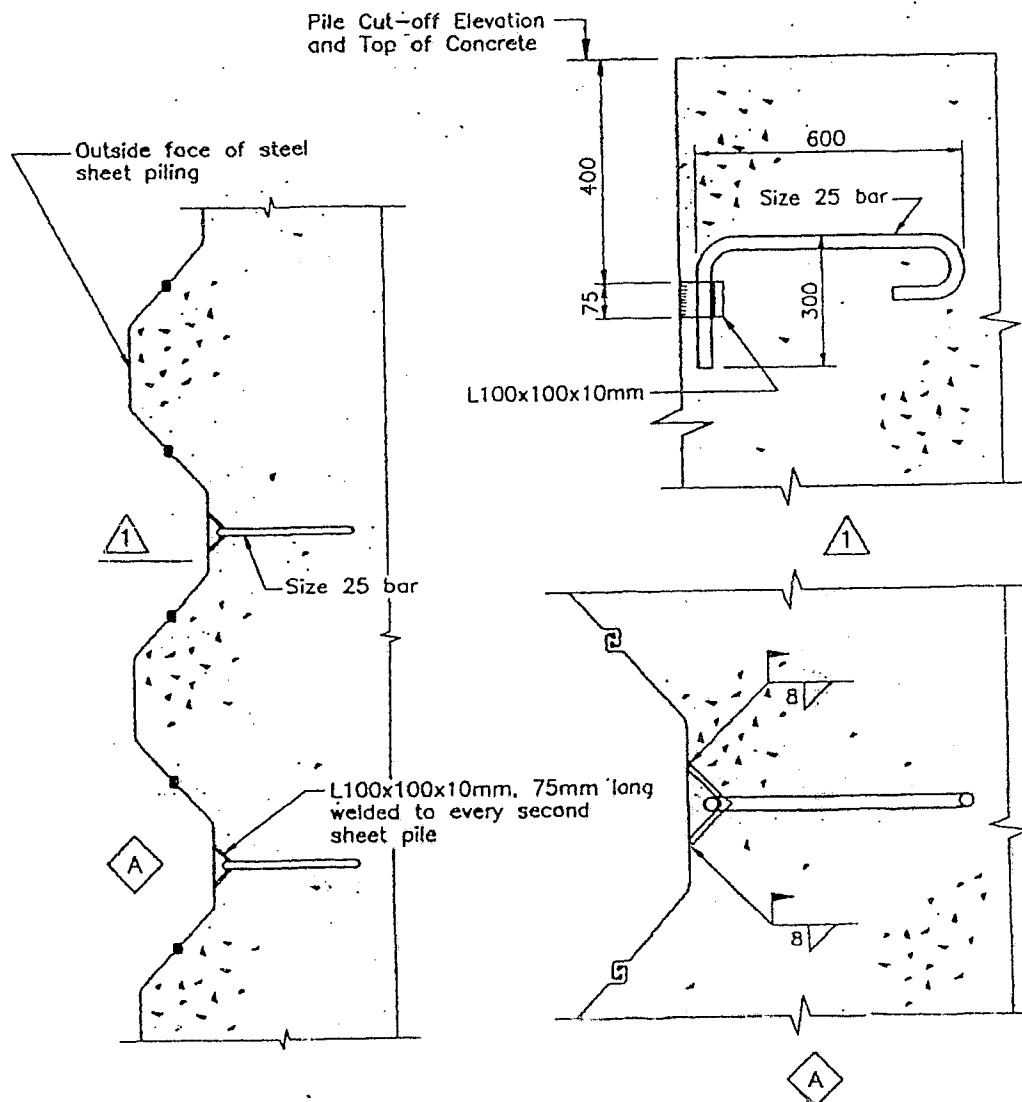


Fig. 6.3 Sheet pile anchor detail [Ontario Provincial Standard Drawing]

Table 3 Screed Elevation

SCREED ELEVATION						
NO	1	2	3	4	5	6
A	229.746	229.742	229.932	229.719	229.719	229.708
B	229.857	229.851	229.847	229.838	229.824	229.812
C	229.768	229.761	229.756	229.745	229.729	229.715

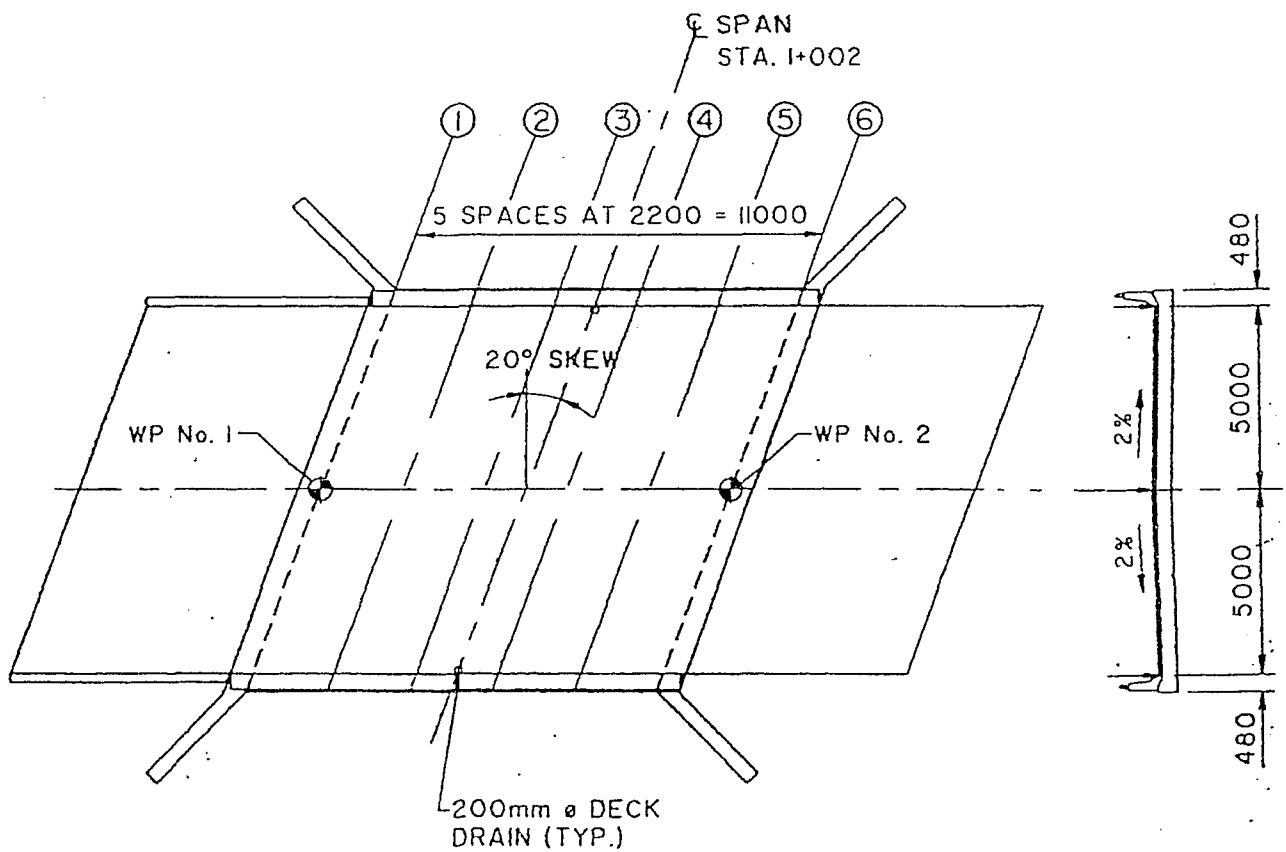


Fig. 6.4 Key plan and screed elevations, 19th Ave. bridge, Markham, Ontario

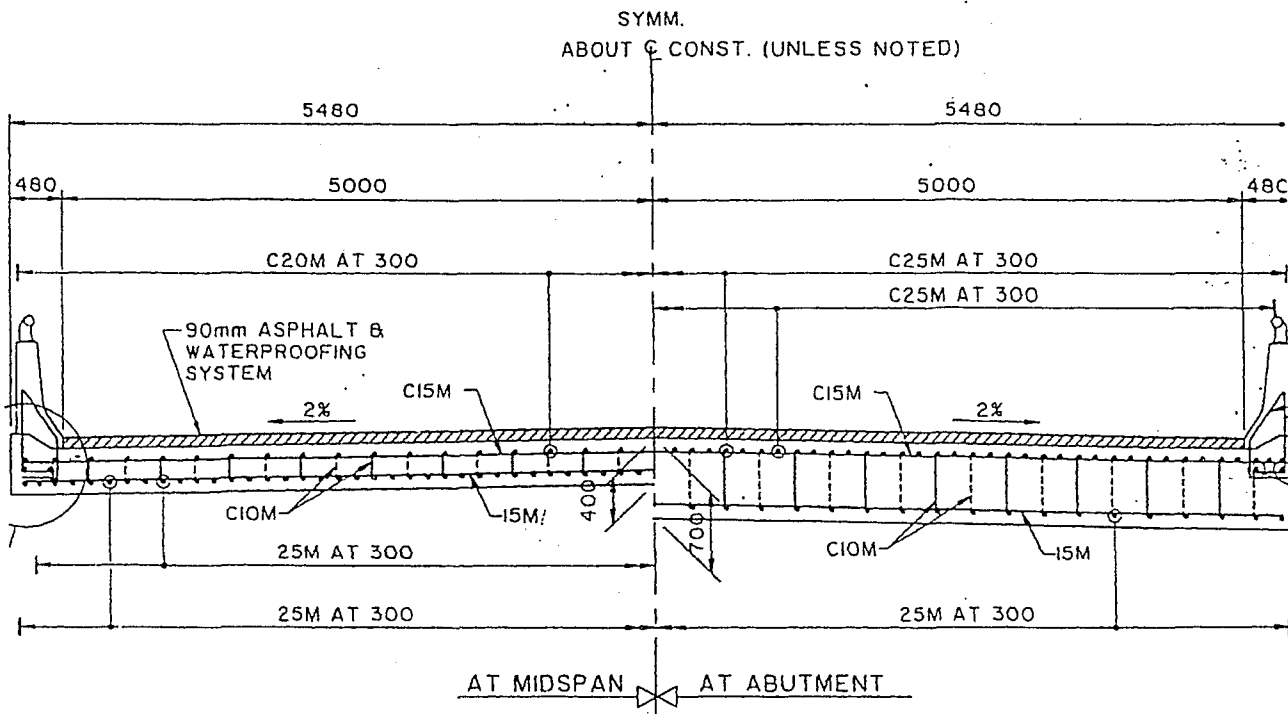


Fig. 6.5 Cross-section of new deck, 19th Ave. bridge, Markham, Ontario

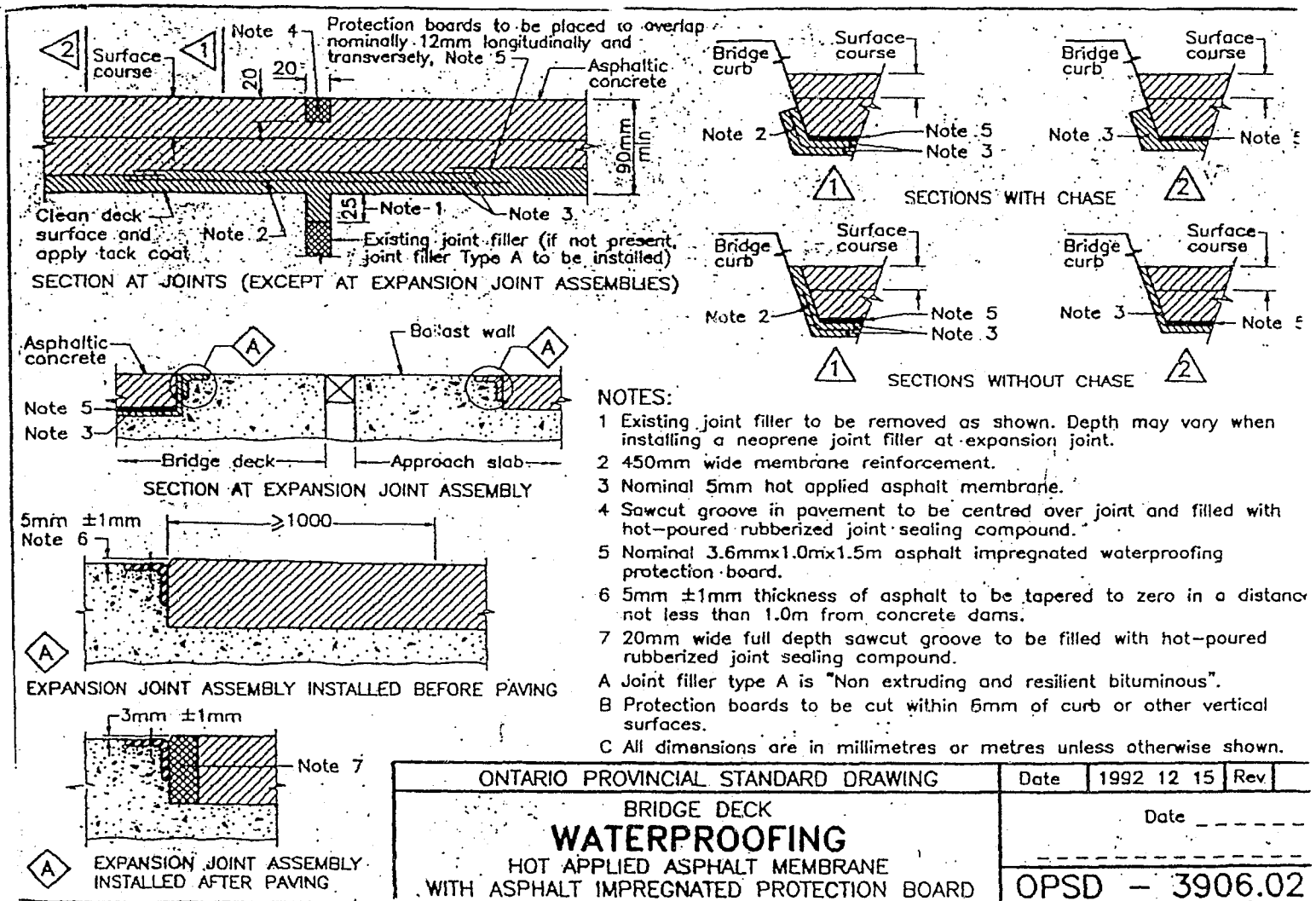


Fig. 6.7 Water Proofing [Ontario Provincial Standard Drawings]

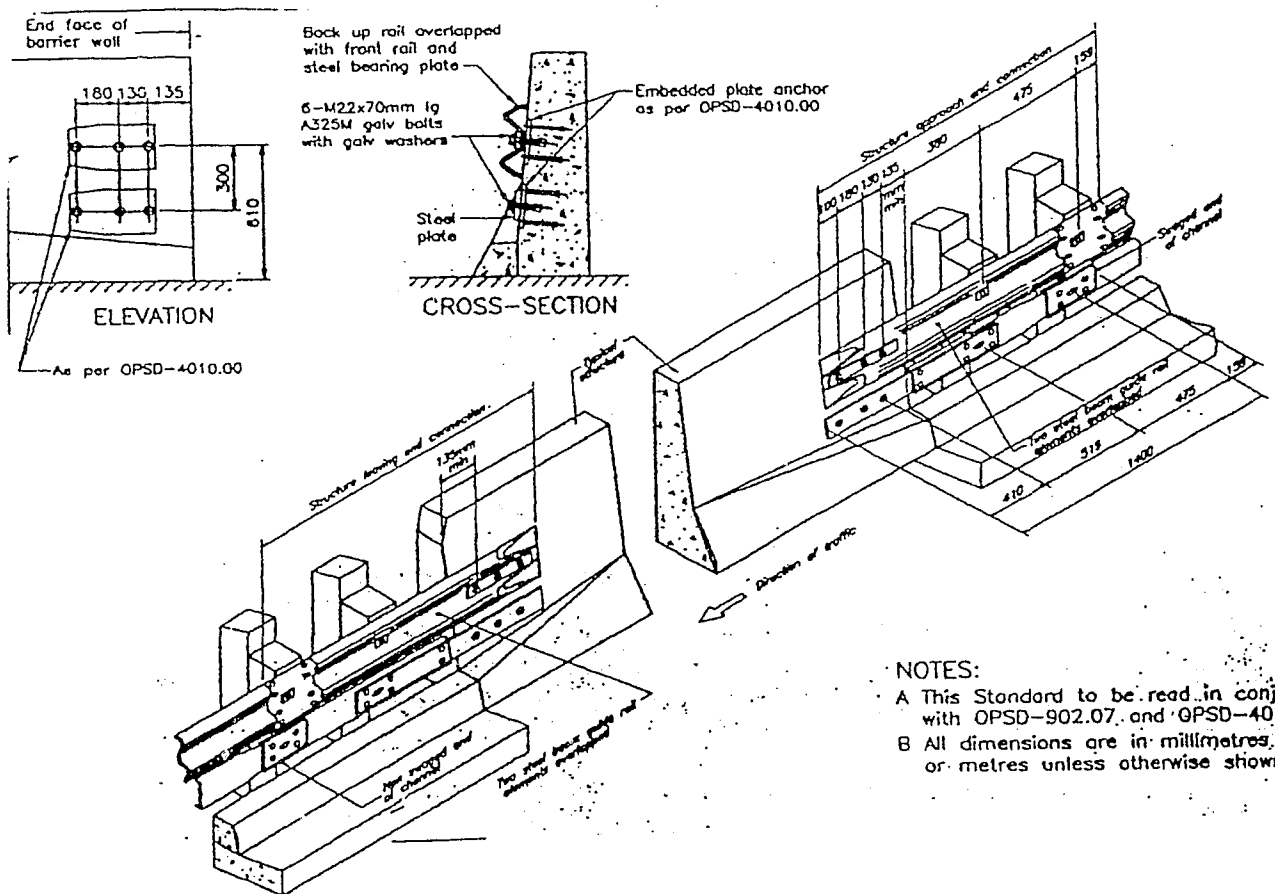


Fig. 6.8 Detail of Barrier Wall and Deck Edge [Ontario Provincial Standard Drawings]

6. CONCLUSIONS

Increasingly greater attention has been paid in recent years to the problem of durability of reinforced concrete structures. The extensive application of concrete materials and their limited life in various media have necessitated a growing volume of repair and restoration of reinforced concrete structures. Considering the difficulties of such repairs, it is imperative to provide an adequate and guaranteed service life of reinforced concrete right at the time of designing and construction of structures. The problem of predicting and designing reinforced concrete structures for a given life can be resolved only by studying the complex processes of interaction between the structural material and the environment.

Concrete is a construction material whose properties, in order to serve as a strong, long-lasting and cost-effective substance, in construction projects such as roads and bridges, must be combined in a technological process that maximizes those properties, a process that takes into consideration the actions of oxidation, temperature, humidity and durability conditions over time. These parameters are of conclusive importance for the long-term stability and strength of concrete structures over time.

Deterioration of concrete bridge decks and parking structures (and even residential roadways) has become a very serious problem in recent years; major repairs are typically needed even in the early years of service life. The extensive use of deicing salts has caused accelerated corrosion of reinforcing steel and deterioration of concrete decks. The products of corrosion occupy considerably more volume than the original steel and exert substantial pressures on the surrounding concrete and cause spalling of the concrete and its fracture.

Most corrosion-related structural distress in concrete is generally caused by electrochemical action due to the formation of local electrochemical or galvanic cells

along surfaces of steel reinforcement. The main factors that influence the onset and rate of corrosion are: the electrical resistivity of the concrete; reduction in pH; availability of oxygen and moisture; and temperature. The reduction in pH of concrete can be a result of chloride salt penetration or carbonation. The inhomogeneities in concrete along the surface of steel rebars are sufficient to set up anodic and cathodic areas in a macrogalvanic electrochemical cell and eventually cause a flow of current. This inhomogeneity causes a difference in electropotential and can arise from many causes, such as differences in chloride concentration, cycles of wetting and drying, differences in pH value, and exposure conditions.

Permeability is considered to be the most important property of the concrete affecting corrosion of the reinforcement. When concrete with high permeability becomes saturated with water, its electrical conductivity relatively increases. Also, the ingress of chlorides, oxygen and carbon dioxide into the surface of reinforcing steel will be relatively easier. High water/cement ratio, inadequate consolidation, and increased bleeding are main factors responsible for high permeability or porous concrete.

Bleeding of freshly placed concrete during the consolidation process can lead to linear depression and settlement cracks along the length of rebars, leading to rapid corrosion. Zones of weakness may be formed in arches of unstable fresh concrete between horizontal bars, which causes surface scaling and loss of concrete cover over reinforcement.

The protective value of the concrete cover over reinforcement against corrosion is attributed to the decrease in diffusion of chemically deleterious substances, the reduction in plastic cracking, and the increased resistance of concrete to bursting forces caused by rust.

Repair and protection of concrete decks are important in order to restore structural and functional integrity of the facility. Providing an impermeable barrier between the concrete surface and any corrosive environment is an attempt to prevent the

penetration of moisture and chloride salts to the reinforcement and to increase the watertightness of the structure. These attempts to improve the durability of concrete have met with varying degrees of success (and failure).

Cathodic protection has proven to be an effective means for the long-term protection of corroding concrete decks. The control of current flow arrests corrosion in the presence of chloride salts, oxygen and water, regardless of pH. The evaluation measures have indicated that the application of cathodic protection system to new and existing concrete decks has been performing satisfactorily. Work is continuing to develop this technology into cost-effective application procedures and to avoid the side effects that may affect the concrete, the steel, and the bond between the concrete and the reinforcement.

Present construction practices can produce both excellent and poor quality concretes. More research work is required to investigate the reasons why concrete deterioration still exists with current construction procedures. The matters of budgets, bidding, and local politics perhaps should be included in any investigation. More effort is needed in the field of improving concrete quality and durability through reliable construction practices rather than concentrating on remedial measures after the fact, such as sealing concrete surfaces. Renewed emphasis on durability of concrete is imperative in design, construction and maintenance of the structure.

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