CHAPTER 1

INTRODUCTION

1.1 Introduction

The history of civil engineering materials, other than stones, goes back as far as Egyptian times. Gypsum was the primary source for producing mortars for construction purposes. The application of lime as a cementious material did not occur until the Greek and Roman eras. Mortars of those days lacked the strength and durability of the primary material for construction, namely, the stone. The first documented approach to develop a new cement that would provide mortar of better durability was made in 1756 by John Smeaton, when he was engaged in a project to rebuild the Eddystone Lighthouse off the coast of Cornwall (27). John Smeaton's structure stood for 123 years before being replaced.

Concrete is one of the most versatile and widely used of all construction materials in the world. The global average production and use of concrete is about a tonne per person per annum. Forecast studies indicate that concrete will continue to be the leading building material in the decades to come, even in the face of changing habits on the one hand and challenges from other non-traditional materials on the other. In the early years of concrete construction, it was thought that the concrete structures would last forever without any maintenance. However, a number of structures built during the last 50 years have suffered durability problems resulting in different degrees of deterioration, while a few cases of total collapse have also been reported. A majority of concrete structures includes embedded reinforcing steel and therefore durability issues must address both concrete and steel.

Reinforced concrete structures form a major part of the engineering infrastructure of all developed countries, and their integrity over long periods of
service is of vital economic importance. The phenomenon of reinforcement corrosion and consequent damage to concrete is increasingly being recognized as one of the menacing durability problems in reinforced concrete structures all over the world. Corrosion claims a staggering US $ 250 billion annually in the United States, which is almost 4.2 percent of its Gross Domestic Product (GDP). India is said to be losing upward of rupees 24,000 crores (approximately US $ 5 Billion) every year on account of corrosion in existing infrastructures. The numerous intangible losses such as the energy needed to manufacture replacements of corroded objects, loss of property and deaths, etc show the havoc wreaked by corrosion.

1.2 Historical Background

Today major constructions are being carried out with reinforced concrete because of its strength and durability. Most of the structures, while in service are subjected to aggressive influences of the environment. The damages made due to corrosion of steel in reinforced concrete structures lead to failure of the elements of the structures or the whole structure.

Safeguarding the reinforced concrete structures against deterioration in coastal environment is a challenging problem faced by the structural engineers, as these structures require major repairs even within five to ten years after their completion.

The 740 m long Princess street flyover, the biggest in Mumbai, located very near to the sea, got badly cracked within 9 years because of saline action. Another bridge located in Namkhana-Amaravathi Road suffered severe corrosion of steel rebar within 10 years. A reinforced concrete pier at Thiruvananthapuram extending 79.25 m into the sea suffered deterioration within 7 years of construction. The Highways Research Station, Madras, surveyed about 80 concrete bridges along the coast of Tamilnadu and brought out many instances of spalling and cracking together with extensive corrosion of reinforcements (26).
A survey of concrete structures conducted by Startfull (1965) along the sea coast of United States revealed that the majority of structures showed evidence of deterioration within 10 years. In the Union of South Africa (Lewis et.al 1959), it has been reported that reinforced concrete structures exposed to marine atmosphere deteriorate in a relatively short period. From the above instances, it can be realized that within 10-20 years, the durability of reinforced concrete structures exposed to sea environmental condition is severely affected. Hence, assuming a design life of about 60 years for such structures seems to be over optimistic and not borne out by facts at least in the specific coastal zone.

It has been estimated (Indian Concrete Journal, 1979), that corrosion of steel takes place at the rate of approximately 0.06mm/year in a carbonated concrete. A large percentage of structures in an environment of chloride is affected by steel corrosion. Brown (1976) has stated that nearly forty percent of the steel produced in United States each year is used only to replace corroded metal (26).

1.3 The Mechanism of Corrosion of Steel Reinforcement

Corrosion, in general terms, means deterioration or destruction of a material due to reaction with its environment. Corrosion of a metal can be defined as a chemical reaction, which returns the metal to compounds that are similar to the minerals from which it was extracted in the first place. Some call metallic corrosion as 'extractive metallurgy in reverse'. Nearly all-metallic corrosion processes are electrochemical in nature; they involve water, which is in the liquid or vapour phases.

The two most common causes of reinforcement corrosion are (i) localized breakdown of the passive film on the steel by chloride ions and (ii) general breakdown of passivity by neutralization of the concrete, predominantly by reaction with atmospheric carbon dioxide. Sound concrete is an ideal environment for the embedded steel but the seashore atmosphere and the increased concentration of carbon dioxide in the present day situations principally due to industrial pollution,
has resulted in corrosion of the rebar becoming the primary cause of failure of reinforced concrete structures.

1.3.1 Theory of Reinforcement Corrosion

There is a distinct difference between the corrosion of bare steel exposed to atmosphere and the steel embedded in concrete. The steel embedded in concrete is well protected because of the good quality of concrete in the cover and its inherent alkalinity. However, reinforcement corrosion can get initiated through one or more effects from the environment. Briefly the nature of reinforcement corrosion mechanism can be attributed to three predominant processes namely chemical, electrochemical and physical.

It is chemical in the sense that the alkalinity of concrete can get reduced to a pH level less than 10.0 by the ingress of either carbon dioxide or chloride, thereby destroying the passivity and initiating corrosion.

It is basically electrochemical because galvanic cells get established by forming locally or generally cathodic and anodic sites resulting in a flow of current with moisture in concrete serving as the electrolyte. In this process, the rate of corrosion is influenced by the supply of available oxygen.

It is physical in the sense that as the corrosion process progresses, the corrosion product (rust) experiences a volume growth, which may be as high as six to seven times the volume of the original metal. This volume growth exerts a physical expansive force on the concrete surrounding the steel. Once the stresses induced by these forces exceed the tensile strength of concrete, cracking of concrete and subsequently spalling of concrete occurs resulting in exposure of reinforcement. If neglected, the loss of the area of steel reinforcement together with the damage induced to crack concrete can lead to catastrophic failure of either a component or the whole structure.
1.4 Transport of Water and Chlorides in Concrete

The concrete pore system filled with air and water solution provides an undesirable path for deleterious substances, which ultimately creates an electrolyte. In matured concrete water movement is affected by cracking and the Hardened Cement Paste (HCP) properties. Aggregate is usually less permeable than HCP, however, its inclusion in concrete creates low density transition zones and makes concrete more permeable. Furthermore, the movement of water in HCP depends on changes in pore structure due to continued hydration, as well as changing solubility characteristics of its constituents. The proposed mechanisms of mass transfer in concrete include adsorption, surface diffusion, vapour diffusion, ionic diffusion and bulk flow. The analysis, even when only one mechanism is being considered, is complicated because of the complexity of concrete pore structure, variation in mixture proportioning and curing and continued hydration.

Permeability can be defined as the ease with which a gas or fluid can flow through a solid. It is obvious that the continuity of the pore system determines concrete permeability. Pressure induced gas flow through concrete follows Darcy's law (31). The disadvantage of testing concrete permeability with gas is that the moisture condition of the sample must be known and carefully controlled. Also, the moisture level must be constant throughout the test material. Gas permeability for low porosity concrete is always greater than the water permeability. Water permeability can be tested by water – vapour diffusion, absorption and rate of absorption, water penetration or saturate flow tests.

1.4.1 Chloride Migration

Chloride ions can migrate into concrete by capillary movement, through cracks, and by diffusion. Capillary movement is a fast method of transport; however it is unlikely for water to migrate this way. First, matured concrete has a discontinuous pore system, and second, concrete holds water in the capillaries, so the driving potential—capillary attraction—is absent. Cracking provides an easy path
way for chloride ions to penetrate concrete cover and reach the reinforcing steel. Structural cracks are aligned perpendicular to the main reinforcement. The subsidence cracks are positioned parallel and directly above the bars. Development of subsidence cracks depends on concrete cover, bar diameter and the slump of concrete. Therefore, the primary modes of transport of chloride ions into the concrete are through diffusion in uncracked concrete and through cracks and by capillary action in cracked concrete.

1.5 Factors Influencing Reinforcement Corrosion

The corrosion process of reinforcement embedded in concrete has two distinct periods namely, initiation period and propagation period. Fig. 1.1 shows these periods schematically as service life of a structure (41).

Fig. 1.1 Service Life Model

The initiation period is the time taken to initiate corrosion, which can be caused either by ingress of carbon dioxide or chloride ions.
During the propagation period, the corrosion progresses at a faster rate depending on the availability of oxygen and moisture.

1.5.1 Corrosion Initiation

The factors which influence the corrosion initiation are the environment, the cover thickness, quality of cover concrete in terms of its alkalinity, permeability and diffusion characteristics, the type of steel and chloride environment present and the presence of cracks.

1.5.1.1 Environment

Broadly the environment can be classified into marine, industrial and marine industrial. It is now recognized that with ever increasing pollution, one of the above environments exists in any given geographical location. The environment, for the purpose of construction of reinforced concrete structures, can further be categorized as different exposure conditions. The different exposure conditions as per the code IS 456-2000 is mild, moderate, severe, very severe and extreme (24).

1.5.1.2 Cover Thickness

It is the primary protection to steel reinforcement. Large cover thickness obviously will delay the initiation of corrosion. However, larger thickness without reinforcement may lead to shrinkage cracking problems. Since the time taken for the aggressive chemicals such as carbon dioxide and chloride to penetrate will be longer, it is necessary to use optimum cover thickness taking into account the structural design as well as environmental aspects.

1.5.1.3 Quality of Concrete

Corrosion initiation is largely influenced by the quality of concrete especially in the cover region. Both chemical and physical parameters of the
concrete are needed to be considered. The primary chemical parameter is its alkalinity expressed in terms of pH value. The physical parameter of concrete that influences corrosion initiation is the permeability of concrete for the entry of water / moisture, carbon dioxide and chloride ions.

1.5.1.4 Type of Steel and Critical Chloride

In reinforced concrete, mild as well as high strength steel conforming to IS 432 (Part 1): 1982 and IS 1786: 1985 are used as reinforcement. Any metal, when exposed, forms an oxidized layer and this is generally a passive layer, which is initially stable and has a protecting ability against corrosion. When this steel is embedded in concrete, the steel together with cement forms a passive layer of Fe\(_2\)C\(_3\), which is highly stable in the initial stages. However, as mentioned earlier, chloride ingress causes instability to this passive layer and makes it to lose its passivity. This occurs at a critical or threshold level of chloride content. This critical level depends on the type of steel (especially based on carbon content of the steel used).

Further the threshold value also depends on the pH value of concrete. For practical purposes the threshold value can be expressed as the percentage of amount of chloride by weight of concrete. Since chloride is a critical chemical to induce corrosion, adequate care is to be taken to ensure that the concrete constituents do not have chloride of unacceptable levels.

The maximum total amount of chloride content in the concrete at the time of placing recommended by IS. 456: 2000 is given in Table 1.1.
Table 1.1 Limits of Chloride Content of Concrete

<table>
<thead>
<tr>
<th>Type of Concrete</th>
<th>Max. Total chloride content in kg/ m³ of Concrete</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete containing metal and steam cured at elevated temperature and prestressed concrete</td>
<td>0.40</td>
</tr>
<tr>
<td>RC &amp; PC containing embedded metal</td>
<td>0.60</td>
</tr>
<tr>
<td>Concrete not containing embedded metal or any material requiring protection from chloride</td>
<td>3.0</td>
</tr>
</tbody>
</table>

1.5.1.5 Presence of Cracks

Any reinforced concrete member may possess micro and macro cracks. Even from design considerations, some cracking is permitted to a width within an allowable limit. However, in very aggressive environments it is preferable to limit the crack width to the barest minimum possible. Besides structural cracking, surface cracking may also occur, due to other phenomena such as thermal effect and plastic and drying shrinkage. The presence of such cracks can drastically reduce the initiation time. This should be adequately taken care of, by adopting good construction practice.

1.5.2 Corrosion Propagation

After the initiation of corrosion, the propagation begins and this period has two distinct processes. Initially, in the propagation phase, the corrosion follows an electrochemical process. Subsequently, the physical process due to which damage to concrete occurs is witnessed. The mechanism and the factors, which influence these processes, are discussed below.
1.5.2.1 Electrochemical Process

In its simplicity, the electrochemical process of corrosion can be considered as the production metallurgy in reverse. Steel is produced from the basic iron ore, which is in oxide form in nature. Energy is spent (added) to make the ore into steel. During the electrochemical process due to corrosion, electrons get liberated, dissipating the energy added, during manufacture and thereby the steel returns to its oxide form.

1.5.2.2 The Physical Process

In reinforced concrete structures, the corrosion of reinforcement is unique in the sense that the corrosion process causes extensive damage to the concrete. The physical process mainly consists of the expansive forces caused by the volume increase of the corrosion products. Once the stress induced by this volume increase exceeds the tensile strength of concrete, cracking occurs. As further corrosion takes place, spalling occurs.

Generally presence of active corrosion process in the reinforcement of a concrete member becomes known only when the symptom of cracking due to volume increase is seen. There is always a time lag between the corrosion initiation and manifestation of the symptom.

1.6 Corrosion of Rebars in Concrete

In reinforced concrete structures rebars that are embedded in concrete do not normally corrode. First, the concrete cover, if dense, intact and thick, forms a barrier, which greatly reduces the penetration rate of exterior environmental agents. Second, concrete is highly alkaline in nature and causes embedded steel rebars to be covered with a passive layer, a thin and dense impermeable film of iron oxide. This film is strongly adherent to the surface and does not allow the anodic reaction to occur, thus making steel passive to corrosion. As long as the passivation layer is intact, the anodic reaction cannot take place.
Due to high concentration of alkalies in the pore water and soluble calcium hydroxide in concrete, the pH value is usually well above 12. The passivation layer on the steel surface is thermodynamically stable as long as the pH of concrete (pore water) remains above 12. The pH of concrete has a significant influence on the corrosion behaviour of steel in concrete. It is generally believed that, the lower the pH of concrete, the higher is the probability of corrosion.

Corrosion of rebars in concrete is an electrochemical process where corrosion cells are generated due to differences in electrochemical potentials. Some areas of the rebar become anode, and some cathode. The metal oxidizes at the anode where corrosion occurs. The typical anodic reaction is:

$$\text{Anode } \text{Fe} \rightarrow 2e^- + Fe^{++}$$ \hspace{1cm} (1.1)

Simultaneously, reduction occurs at cathodic sites. Typical cathodic reaction is:

$$\text{Cathode } \frac{1}{2} O_2 + H_2O + 2e^- \rightarrow 2(OH)^-$$ \hspace{1cm} (1.2)

The hydroxyl ions, OH, that arrive at the anodic area, electrically neutralize the Fe $^{++}$ ions dissolved in pore water and form a solution of ferrous hydroxide as shown:

$$\text{Anode } Fe^{++} + 2(OH)^- \rightarrow Fe(OH)_2$$ \hspace{1cm} (1.3)

The product further reacts with available oxygen and water and forms water insoluble red rust:

$$\text{Anode } 4 \text{Fe(OH)}_2 + O_2 + 2H_2O \rightarrow 4 \text{Fe(OH)}_3 \text{ (Red Rust)}$$ \hspace{1cm} (1.4)

Red rust is not the only product of corrosion of steel in concrete, but also compounds such as black rust ($Fe_3O_4$), green rust ($Fecl_2$), and other ferric and ferrous oxides, hydroxides, chlorides, and hydrates are also formed.
For example:

$$3 \text{ Fe} + 8(\text{OH})^- \rightarrow 4 \text{ H}_2\text{O} + 8 \text{e}^- + \text{Fe}_3\text{O}_4 \text{ (Black Rust)}$$

The composition of products formed depends on the availability of pore water, its pH and oxygen supply. The basic process of reinforcement corrosion (5) in concrete is explained in Fig. 1.2 (12).

The factors, which influence the electrochemical process, can be summarized as follows:

- pH value
- Chloride content
- Moisture within the concrete influenced by the humidity of environment or direct contact with water
- Oxygen supply, which controls the rate of corrosion

In addition to the above factors, electrical resistivity of concrete also influences the electrochemical process.

Fig. 1.2 Basic Corrosion Process of Reinforcement in Concrete
The black rust volume is twice as large as that of steel, and red rust volume is four times as large. The increase in volume causes tensile stresses in concrete, which leads to cracking and spalling of cover concrete. Therefore, Corrosion products are very dangerous to concrete elements because their volume is much larger than the volume of the original steel rebar.

As mentioned above, chloride ions accelerate corrosion of steel in concrete. The mechanism of action of the chloride ion is not entirely understood. The general opinion is that the chloride ion acts as a catalyst in corrosion reactions. When the concentration becomes large enough, ferrous products form an acid solution with chlorides, which neutralizes the alkaline concrete environment and further enhances corrosion liability. Ferrous chlorides being more soluble than the oxides move away from the reinforcing steel and expose new areas to the corrosive environment.

1.7 Types of Corrosion

Pitting and general corrosion are the two most common types of corrosion of steel reinforcement in concrete. Pitting corrosion occurs when only a small area of steel loses its passive layer, usually due to high concentration of chloride ions. A large cathode area and a small anode area resulting in accelerated corrosion at the pit characterize pitting corrosion. General corrosion occurs when the pits grow together and anode areas are large and the cathode areas are small. The corrosion rate is much slower when compared to pitting corrosion because of the lower cathode to anode area ratio.

Another classification is based on relative position of anodic and cathodic sites. This relative position depends on a potential difference between the anodic and cathodic sites. The larger the potential difference, the further apart the anode and the cathode will be. If the two sites are in close proximity to each other, micro cell corrosion occurs. Macro cell corrosion occurs when the anode and the cathode sites are farther apart and a large potential difference between the anode and cathode
exists. Slater (at) suggested that accelerated corrosion of bare steel reinforcement in the decks with bottom mat of coated steel is a result of macro cell corrosion. In most cases however, since macro cell corrosion requires larger potential difference than the micro cell corrosion, it is more likely for the micro cell to be a dominant type.

1.8 Coating on Rebars

Corrosion of steel reinforcement in concrete is one of the major problems with respect to durability of reinforced concrete structures. Failures of concrete structures due to corrosion of rebars have been observed in Norway. Within 25 years of construction, the reinforced concrete structures at a seaside resort at United Kingdom had badly cracked due to the corrosion of rebars. Use of rusted reinforcement rods coupled with exposure to corrosive environment leads to premature failure of reinforced concrete structures (33).

The durability of marine structures is adversely affected within 20 to 30 years of its commissioning, i.e. the actual trouble free life of structures in aggressive environment is only about one fifth of the design life, unless some effective protective measures are taken at the initial stage itself. India with its nearly 5600 km of coastal line has to maintain many strategic reinforced and prestressed concrete structures such as bridges, offshore structures etc (33).

The main reason for this type of damages in concrete is chloride ions in association with oxygen and moisture. The impure materials used for concreting, mixing admixtures containing chlorides like calcium chloride or de-icing salts such as sodium chloride for colder environment are the main sources of chloride in coastal structures. A protective anti-corrosive treatment to steel reinforcement before it is embedded in concrete can guard against and delay the process of corrosion.

The chloride ions diffuse through concrete and depassivate the gamma iron oxide ($\alpha$Fe$_2$O$_3$) film on the rebar surface leading to pitting and dissolution of iron in
the steel reinforcement. This will lead to cracking, spalling and collapse of concrete structures. In order to avoid such types of failures, many protective methods have been tried and adopted all over the world. For new concrete structures, application of protective coatings on steel rebars, alternate depassivating materials, cathodic protection, surface coatings on concrete surfaces, addition of corrosion inhibitors to concrete, surface sealants, etc have all been tried to give additional protection.

For old structures, electrochemical removal of chloride or realkalization can be used instead of the traditional method of removing chloride-contaminated concrete. Among the above methods, an easy and economical protective method is application of coating over steel surface. This is bound to delay the corrosion process.

1.9 Life Prediction

During their lifetime, structures are subjected to external actions or agents, which in time may alter their state from a safe to a failure or damaged state. One of the processes that may trigger the onset of corrosion of steel embedded in concrete is the ingress of chloride ions, which eventually reach the reinforcement causing the rupture of the passive film. A reinforced concrete structure may lose its serviceability either due to abnormal deflection or cracking.

The structure’s use may be terminated by either the deflection or cracking exceeding the permissible limit or the structure or element reaching the collapse limit state. Thus the life of a corrosion affected structure can be quantified if a corrosion deterioration model is proposed based on a postulated failure at either serviceability or collapse limit state. Concrete quality, workmanship, reinforcing steel cover, environment and maintenance each have significant influence on the service life period of reinforced concrete.
1.10 Review of Literature
1.10.1 Related to Historical Background

The following chart (Fig.1.3) indicates the review of literature of research works carried out on corrosion influenced by various parameters.

![Diagram of Historical Development in Corrosion Testing and Evaluation]

**Fig. 1.3 Summary of Literature Review on Historical Background**

**Bailey Tremper** (1947)(8) studied sixty-four small reinforced concrete beams under loaded condition. After ten years of exposure to outside atmosphere the steel reinforcements were removed from the concrete and then examined for the extent of corrosion. Corrosion was observed in the cracked region in the beams. It was concluded that cracking is a major factor in encouraging steel corrosion provided the concrete is of adequate quality to resist disintegration.

**Spellman** et. al. (1970) (48) have studied the behaviour of 710 Nos. of reinforced concrete blocks in a saturated sodium chloride bath under partially submerged condition.
From the tests, it was shown that a sufficient quantity of chloride absorbed by concrete causes the steel to change from a passive to an active state and leads to corrosion. The test results showed that increasing the cement content and increasing the time of water curing delayed the onset of active potential for causing corrosion.

Shinzo Nishibayashi et. al. (1980) (46) carried out a study of reinforced concrete in sea-water environment. Tests were carried out with the variables such as type of cement, water/cement ratio, the mixing water (fresh or seawater) and the age of immersion. From the test results, they have concluded that the seawater resistance of reinforced concrete using seawater-resisting cement is considerably higher compared to that of concrete made with Ordinary Portland Cement.

Kiyashi Okada et. al. (1980) (29) carried out a study of corrosion of reinforcing steel in concrete using electrochemical methods. The tests were conducted by continuous immersion of specimens over a constant period in the seawater and also by alternate wetting and drying method. They concluded that with increase in water/cement ratio of concrete during casting, the potential of reinforcing steel becomes less and the electrical resistance of wet concrete becomes lower. They further concluded that wetting and drying cycles make the corrosion rate higher than the continuous immersion.

Al-Sulaimani et. al. (1990)(2) investigated the influence of corrosion and cracking on bond behaviour and strength of reinforced concrete beam by conducting pull out and beam tests. Bond behaviour is studied at different stages of reinforcing bar corrosion i.e. at non – corrosion, cracking and post cracking levels. These stages of corrosion have been achieved by impressing direct current for an increasing period on the reinforcing bar embedded in the pullout or beam specimens. From the above tests, it was found that the bond strength increased with corrosion up to a certain amount and up to a certain limit.
Escalante et. al. (1990)(17) conducted tests to find the relationship of pH in terms of chloride and oxygen concentrations. He showed that a drying cycle, which locally concentrates chlorides and oxygen, initiates the corrosion of steel in concrete. Once corrosion is initiated, the pH at the anodic areas decreases, allowing corrosion to proceed more easily. Oxygen controls the rate of corrosion, but chloride affects the number of sites where corrosion gets initiated.

Hansson et. al. (1990) (21) investigated the influence of a number of factors on the critical concentration of chloride necessary for initiation of corrosion of steel embedded in concrete. The variables investigated include environmental conditions during curing, water/cement ratio, cement type, surface condition of reinforcing steel and type of salt. The rate of chloride penetration, the chloride concentration in the mortar adjacent to the steel at the onset of corrosion and the subsequent corrosion rate have all been measured to determine the influence of these variables.

Rasheeduzzafar et. al.(1992) (43) studied the effects of concrete and steel parameters such as concrete cover, concrete quality and bar size on corrosion of steel. These parameters have a significant effect on corrosion initiation and corrosion cracking. They have quantified the effect of these three parameters. It is found that the cover to bar diameter (c/d) ratio is a more definitive protection parameter against corrosion cracking than either cover or bar diameter alone.

Arup et.al. (1993) (6) found good correlation between rapid permeability and resistivity measurements. Andrade and Sanjuan (1994) (4) studied the rapid permeability test using a modified test with a 12 V applied voltage for different sample sizes and solutions. However, their conclusions may apply to the rapid permeability test as well. The authors reported that highly concentrated solutions are not recommended because the chloride activity decreases, but also excessively diluted solutions may not provide adequate driving force and result in inaccurate results. The authors also found that the resistivity of concrete is a promising parameter for mass transport characterisation.
In another experiment Zhang and Gjorv (1994) (62) used electrochemical test method of rapid permeability, for chloride ion migration determination and found that the concentration of chloride source solution has a significant influence on the results and a correction factor needs to be introduced. Feldman et. al. (1994) (18) and coworkers investigated influence of changing parameters on the rapid permeability results. The factors included temperature, AC impedance, initial DC current, etc. In addition, chloride ion profiles were monitored during polarization. The major conclusion was that the test induces change in the concrete pore structure and its resistivity. The authors suggested a simple measurement of initial current or resistivity as a replacement for the rapid permeability test when concrete with ASTM type I cement is used.

Fick’s second law of diffusion and Danckwert’s solution was used by Tumidajski (1995) (54) to model chloride diffusion. He obtained a good fit of the solution to experimental data from Page and co-workers with the diffusion coefficients of 125 and 49 sq.mm / year, but may be an order of magnitude lower or higher depending whether a pozzolan additive is added or a low quality concrete is used, respectively.

In another study, Tumidajski and Chan (1995) (54), (1996) (53), found the chloride diffusion coefficient being dependent on both time and chloride concentration/depth. The authors observed a significant decrease of chloride diffusion coefficients; however their analysis was based on a solution with surface concentration being time independent - constant. On the other hand, Frey et.al. (1994) (19) found the diffusion coefficient to be dependent on porosity but not on chloride concentration. Mangat and Malloy (1994) (37) studied the chloride diffusion coefficient and found it to be strongly dependent on time of exposure to chloride environment.

Chloride concentration profiles in a concrete cylinder were modeled by Arora et. al. (1996) (5). The authors showed that a model with constant surface concentration and a constant diffusion coefficient could be successfully used to predict the chloride concentration profiles, but found it applicable only for short periods of time. Uji et. al.
had appreciable corrosion concentrated in the structure located above the wave section but had no corrosion in the lower part submerged below water level.

Locoge et. al. (1992) (34) Studied the influence of micro cracks on transport of chloride ions by diffusion and relationship between cracking specific area and flow rate of chloride ions. The effects of cracking and self-healing on chloride migration on a w/c ratio of 0.4 concrete were investigated by Jacobsen et. al. (1996) (25). The internal cracking was achieved by exposing specimens to freeze-thaw cycles and self-healing was simulated by immersing specimens in lime-saturated water. A reduction of 28 to 30 % in chloride migration was observed in the self-healed concretes when compared to newly cracked concrete.

1.10.3 Related to Coating on Steel

Yeoh et. al. (1994) (60) has studied the influence of corrosion of reinforcement in repaired concrete specimens. This investigation provides comparative data on performance of both coated and uncoated bars in preventing corrosion. The concrete exposed to normal environment and that exposed to deicing salt were considered. Corrosion was assessed by half – cell potential method and visual examination. It was found that the half – cell potentials of reinforcement in the repaired specimens became more negative with time. As expected, it was seen from the visual assessment that corrosion activity on the uncoated bars was more extensive than on the coated bars.

Kumar et. al. (1996) (33) have carried out a study on various aspects related to the mechanization of Cement Polymer Composite Coating (CPCC) for corrosion protection of rebars. The data on corrosion resistance, stress corrosion, cracking resistance test, bond etc. have also been discussed. They have concluded that the CPCC system has the following advantages.
Being cement based in composition, it is more compatible in concrete medium. The coating has high corrosion resistance against chlorides. It has good bond strength and hence bond between coated rod and concrete is not affected.

Srinivasan (2000) (49) has presented a methodology for a systematic insitu testing for identification and appraisal of corrosion in reinforced concrete structures and also discusses the various corrosion control methods. He concluded that epoxy coated bars offer excellent protection to corrosion, but the effect of bond is to be ascertained. Presence of holidays should be checked for reducing severe localized corrosion. Suitable design guide lines are required for designing the structures with coated reinforcement with regard to development length, cover thickness etc.

1.10.4 Related to Mineral Admixtures on Corrosion

Many studies have been performed on mineral admixtures and their influence on chloride permeability and diffusion characteristics. Studies varied in type of mineral admixture used, percent cement replacement, curing and exposure conditions and others. In general, concrete with mineral admixtures exhibit reduced permeability and diffusion coefficients are lower than that for the Ordinary Portland Cement concrete.

Zhang and Gjorv (1991) (61) reported that when silica fume replacement by about 10 % is made, chloride diffusivity reduces to such extent that the w/c ratio is of a lesser importance.

An extensive study on concrete with slag cement and silica fume was performed by Ozyildirin (1993) (40). The rapid permeability results indicate much better performance of specimens with slag/silica fume /Type II cement than with slag/silica fume /Type III cement and the corresponding 28 day Coulomb values were from 471 to 824 and from 791 to 1195 respectively.
Naik et al. (1994) (38) studied the influence of fly ash percentage replacement on water permeability and found that for up to 50% cement replacement, chloride permeability was reduced, but this was not the case for higher percentages of cement replacement.

Torii and Kawamura (1994) (52) investigated concrete with various percentages of silica fume. From the results of AASHTO-T-277, the authors reported that chloride ion permeability into mortar containing 10 and 15% silica fume drastically decreased with the distance from the sample surface, but this was not the case with the OPC samples. The authors concluded that AASHTO T-277 underestimates the 'real chloride ion permeability' in concrete samples containing silica fume or fly ash. However, they did not comment on eventual influence of the shrinkage related surface micro cracking in the SF samples. This might have explained the relatively high concentration at the shallow depth (0-10 mm) and very low or zero concentrations at higher depths (50 mm). Such a comment was made by Frey et al. (1994) (19). Based on the results of their study on the reduction of the diffusion rates of chloride ions in concrete with addition of granulated blast furnace slag or fly ash, the authors said that micro-cracks may be present due to shrinkage.

1.10.5 Related to Life Prediction

A corrosion deterioration model for bridge structures was proposed by Cady and Weyers (1984) (13). This general representation of deterioration versus time relationship can be divided into three stages: diffusion, corrosion and deterioration. The diffusion period is the time when chloride ions penetrate concrete cover until their concentration, at a rebar level, reaches the corrosion threshold level. The second period in model is called the corrosion period. At this stage the corrosion of the reinforcing steel initiates and progresses until first cracking occurs. Factors such as bar size, it's spacing and concrete cover above the steel determine whether inclined or delamination cracking occurs (1979) (9).
Andrade et. al. (1990) (3) made an attempt to implement the values of corrosion intensity, which have been measured in laboratory tests, for the service life prediction analysis for corroding structures. The model on service life suggested by Tuutti (1980) (56) was considered and only the propagation period model has been analysed.

The average service life of bridges in the United States, including rehabilitation and the component replacement, was estimated to be 70 years. Major rehabilitation of a bridge takes place when the structure is about 35 years old (1982) (11). The design life for buildings and other structures in Europe is 50 years, while bridges are expected to last 120 years (1992) (14). Under these conditions, predicting the service life of concrete structures, which includes present knowledge of their deteriorated condition, became an important subject in making the most cost-effective decisions concerning future management of these structures.

The last period in the Cady-Weyers (1992) (58) deterioration model is the deterioration phase. In this period, the bridge deck continues to deteriorate until the time when repair or rehabilitation is required. Factors such as delaminations, spalling, patches and cracking influence decisions regarding the time of repair or rehabilitation. Based on a strategic highway research program report, the end of service life is determined when the damage of the worst traffic lane reaches 9.3-13.6% of the area.

Other Models

Browne (1982) (11) proposed a basis for design, repair and inspection procedures by predicting the time of corrosion onset using the diffusion rate for chlorides to reach the reinforcing steel, \( t_1 \), and the time from the activation of corrosion of steel to the presence of damage in the concrete structure, \( t_2 \). Accordingly, corrosion of steel causing damage, \( d \), in the existing concrete structure should be described using the following equation:

\[
d = f(t_1 + t_2) \quad 1.6
\]
1.11 Objectives

1. To study the effectiveness of different types of coatings on the surface of the steel reinforcement for reducing the probability of rebar corrosion, under similar exposure conditions.

2. To investigate the effectiveness of rice husk ash as a mineral admixture to concrete in resisting rebar corrosion by adopting partial cement replacement.

3. To study the effect of corrosion under stressed and unstressed conditions.

4. To predict the service life based on compliance with codal requirements at serviceability conditions and for avoiding attainment of collapse load.

1.12 Scope of the Investigation

- To examine the corrosion liability of steel rebar embedded in concrete under the following conditions:
  1. When the reinforcement is uncoated.
  2. When the reinforcement is provided with different surface coatings.
  3. When the concrete environment is modified using, Rice Husk Ash as corrosion inhibitor.
  4. When steel rebar is embedded in various grades of concrete.
  5. When the steel is under different states of stress with respect to cracking.

- To predict the service life of beam specimens based on ultimate and serviceability conditions.

1.13 Flow Chart

A flow chart covering tests completed under the scope for studying different types of protection for rebar is presented in Fig.1.4.
Fig. 1.4 Details of the Present Investigation