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PREVENTION OF RCC STRUCTURES DAMAGE BY CORROSION

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ABSTRACT

As structures are the base of engineering, hence to design a structure with the least errors is the basic requirement of engineering. Practically it is not possible to maintain the proper balance of the structure with the environmental changes. Hence with the changes in the climatic conditions the structure gets affected. One of the major problems regarding the RCC structures is corrosion. The Damages caused by corrosion of RCC structure has been recognized as one of the major problem affecting service life of structure. But corrosion cannot be stopped completely. It can be reduced if certain practices to combat corrosion are applied. Permeability is the gateway of corrosion. Hence corrosion - permeability interaction has been presented in this paper. Water proofing has been suggested as preventive solution for concrete structure exposed to corrosive environment. Structures are damaged due to corrosion in concrete. Suitable and effective repair system is unavoidable protective solution for corrosion affected concrete structure. In the present paper the authors have made an attempt to present preventive and protective solution of corrosion in concrete through chemistry. Repair material, its criteria, various techniques and methodology has also been discussed. The approach is also illustrated by presenting case studies also.

I. INTRODUCTION

Though concrete is quite strong mechanically, it is highly susceptible to chemical attack and thus structure gets damaged and even fail unless some preventive measures are adopted to counteract this and thereby increasing the durability of structure. In the case of Reinforced concrete structure the ingress of moisture or air may lead to corrosion of steel, cracking and spoiling of concrete cover thereby reducing durability of concrete structure. Repair has been suggested as the protective solution for damaged structure due to corrosion. The successful repair of concrete in the long term depends on a number of factors including correct diagnosis, careful selection of appropriate repair material and accurate methodology of material application. The main focus of this paper is to highlight the methodology of repair of damage due to corrosion, criteria of repair material used and the mechanism of preventive and protective solution of corrosion affected concrete structure illustrating case studies.

II. FACTOR AFFECTING REINFORCEMENT CORROSION

- Effect of aggressive anions

Chloride in concrete may be present as Acid soluble chloride, chemically bound chloride with hydration products of cement and free or water soluble chloride within the pore solution of concrete. Generally, the concentration of free chloride ions (Cl-) influences the corrosion process. It is reported that the corrosion rate increases with an increase in chloride content. However, the change in pH is insignificant due to change in chloride content of concrete .The risk of reinforcement corrosion associated with the level of chloride content in both uncarbonated and carbonated concrete is presented.

- Effect of carbonation and entry of gaseous pollutants

The pH of the concrete is reduced by the carbonation and entry of acidic gaseous pollutants such as SO2 and NO2. The fall in pH to certain levels may cause commencement of reinforcement of corrosion, loss of passivity of concrete against rebar corrosion and catastrophic corrosion indicated in table.

Table- State of Reinforcement Corrosion

pH of concrete	State of reinforcement corrosion
Below 9.5	Commencement of steel corrosion
At 8.0	Passive film on the steel surface disappears
Below 7	Catastrophic corrosion occurs

- **Effect of Bacterial action**

  Aerobic bacteria may aid in the formation of differential aeration cell which will lead to corrosion. In sewer concrete, the anaerobic bacteria produces iron sulfides which too enables the corrosion reaction to proceed even in absence of oxygen9. The bacteria decrease the amount of cover by disintegration of cementations material.

- **Effect of w/c ratio**

  Basically w/c ratio control strength, durability and permeability of concrete and does not control the rate of corrosion but 'permeability' which is a function of w/c ration affects the corrosion of rebar. The depth of penetration of particular chloride threshold value increases with an increase in the w/c ratio. Carbonation depth has been found to be linearly increasing with an increase in w/c ratio. The oxygen diffusion coefficient is also found to be increasing with an increase in the w/c ratio. In a study it is observed that the permeability of hardened cement paste is increased 100 fold by increasing the w/c ration from 0.35 to 0.45 and the time of initiation of reinforcement corrosion in a sample with a w/c ration 0.4 is 2.15 to 1.77 times more as compared to a sample with a w/c ratio of 0.55, under accelerated corrosion testing.

- **Effect of cover over reinforcing steel**

Risk of reinforcement corrosion with low cover thickness, has been reported by various researchers. The cover thickness has a remarkable effect on rebar corrosion due to penetration of chloride or carbonation. This effect of corrosion is limited within the time of casting to the time at which the rebar is depassivated and corrosion is started. The rate of corrosion, once it has started, is independent of the cover thickness.

III. PROTECTIVE SOLUTION AND ITS MECHANISM

The damage to concrete due to corrosion of reinforcement has been recognized as one of the most serious causes for durability problem over the last several years. Research has given rise to a variety of concrete corrosion protection measures in both new concrete and in repair of damaged concrete. Epoxy based thin coating has been found to be extremely effective except few drawbacks. The innovative method of corrosion protection is the development of a two component anti-corrosive coating of rebars which has all the positive features of epoxy coating excluding all the short comings of the same. For corrosion not to occur it is necessary that the alkalinity around the rebar is high. The various components have been so designed in this cementitious product that the alkalinity around the rebar is increased to the tune of 13. Specific reactive fillers reduce the permeability of protective coating over rebar. Selective polymer in the formulation increases the bond between coatings and rebar and also makes the coating more impenetrable to polluting gas. Thus the increased corrosion inhibiting property of the coating helps in achieving a durable and successful repair of corrosion affected concrete structures.

The degree of protection provided by concrete may be reduced when a reinforced structure is exposed to de-icing salts , acidic gases, or immersed in sea water. Ingress of aggressive species, e.g, chloride ions or carbon dioxide, can change both the concrete and its pore solution chemistry, leading to depassivation of the reinforcement, and therefore, accelerating the corrosion where metallic Fe at the anode is oxidized to ferrous ions ($Fe2^{+}$)

$Fe \rightarrow Fe^{2+} + 2e^-$

Initially, this reaction is balanced by cathodic reduction of dissolved oxygen to hydroxyl ions

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

The Fe^{2+} combined with Cl^- drive to the anode by the corrosion current and form the H_2O soluble ferrous chloride ($FeCl_2$):

$Fe^{2+} + 2Cl^+ \rightarrow FeCl_2$

Some $FeCl_2$ migrates out of the corrosion pit and reacts with the cathodically formed sodium hydroxide (NaOH) to produce a ring of a white precipitate of ferrous hydroxide $Fe(OH)_2$:

$FeCl_2 + 2NaOH \rightarrow Fe(OH)_2 + 2NaCl$

The $Fe(OH)_2$ is soon converted to hydrated ferric oxide ($Fe_2O_3.H20$), also known as ordinary red-brown rust, and to black magnetite (Fe_3O_4), followed by the formation of green hydrated magnetite ($Fe_30_4.H_20$):

$4Fe(OH)_2 + O_2 \rightarrow 2H_2O + Fe_30_4.H_20$

$6Fe(OH)_2 + O \rightarrow 4H_2O + Fe_30_4.H_20$

$Fe_30_4.H_20 \rightarrow H_2O + Fe_30_4$

A tubercle is formed at the pit orifice, which consists mainly of Fe_30_4 and $Fe_20_3.H_20$. This tubercle hinders the replenishment of dissolved O_2 into the pit interior and prevents intermixing of the electrolyte trapped inside the pit with the bulk solution resulting in local acidification. This type of localized attack, when coupled with a large passive area of reinforcement can cause structural damage.

IV. PROTECTIVE MATERIAL

RCC protection is a complex system. Repair is the only way to protect the corrosion affected concrete structure. In carrying out repair we attempt to create a bond between old structure and new repair materials which will restrict the shrinkage in repair material. A good repair mortar should have following properties.

- Lowest shrinkage
- High tensile creep
- Low modulus of elasticity
- Low coefficient of thermal expansion
- Impermeability.
- High tensile and flexural strength
- High chemical resistance
- Low water absorption
- High bond strength
- High flexibility

By adding accurate granulometry of aggregate, keeping water - cement ratio to the lowest possible, suitable quality of cement for the job and appropriate polymers in right proportion we may incorporate the above properties to repair mortar to achieve a durable repair system. For smaller repair job and where cement based products are either technically unsuitable or will take too long to cure, epoxy mortars are often the most cost effective solution.

- EPOXY-COATED REINFORCING STEEL

- The performance of epoxy-coated reinforcing steel is enhanced by quality concrete and adequate cover.
- Epoxy coatings lose their adhesion to steel reinforcement when exposed to moisture. Whether this adhesion loss is a direct cause of corrosion damage is under debate.

• Performance of epoxy-coated reinforcement is related to the number of defects (holidays) in the coating. These defects directly effect the electrical resistivity of the reinforcement.

• Most problems that have been reported with epoxy-coated reinforcement have occurred in environments where the concrete is continuously wet, yet oxygen is still available (splash zones on piers, or areas of high humidity). Often these environments have high average temperatures.

• There is little doubt that the time to corrosion-induced cracking is increased in many concrete structures containing epoxy-coated reinforcement over the time to corrosion-induced cracking in bridge decks with no protective measures.

- Galvanized Reinforcement

Hot-dipped zinc-coated steel reinforcement may provide superior performance to that of uncoated steel. Zinc-coated, or galvanized, bars are produced by a hot-dip process. This consists of cleaning the steel bars by pickling, and then immersing them in molten zinc. Galvanized bars are dipped in a chromate bath after coating to passivate the zinc surface and to prevent it from reacting with the hydroxide in fresh cement paste. Like steel, zinc has corrosion products that occupy more volume than the original metal, and, as a result can cause concrete to crack. An advantage of galvanized reinforcement is that, when zinc corrodes sacrificially, a hydrated oxide [$Zn(OH)_2$] is formed on the surface that acts as an electrical insulator. This insulator is thought to form a barrier layer at active corrosion sites that will prevent further corrosion from occurring . The study was expanded to compare epoxy-coated reinforcement to galvanized and uncoated reinforcement. Specimens were constructed using galvanized, epoxy-coated, and plain "black" steel. The specimens were then placed outdoors in a testing facility. Dikes were built around the edges of the specimens to retain water and a saltwater solution was applied to the surfaces on a regular basis throughout the winter months.

- BARRIERS

Low Permeability Concrete-Probably the most important requirement for any reinforced concrete structure is the use of good quality concrete. Concrete contains many interconnected pores, which form a network of channels that allow water and oxygen to infiltrate the material. Generally, a low w/c ratio and good consolidation results in fewer and smaller pores, as well as fewer voids, and a subsequent reduction in permeability. In addition to slowing the ingress of water, oxygen, and chloride ions, reduced permeability leads to a reduction in electrical conductivity since fewer chloride ions are carried into the concrete by moisture.

Mineral Admixtures

A pozzolan is a material that contains silica that is able to react with calcium hydroxide. Advantages to using pozzolans in concrete include improved workability of harsh mixes, lower heat of hydration, and improved permeability and durability of hardened concrete. When pozzolans are used in concrete, the rate of early strength gain is often reduced, but over time, the strength of the concrete is improved. However, if the water requirement of a concrete mix is increased by the addition of a pozzolan, an increase in drying shrinkage and creep should be expected.

There are many different materials that can function as pozzolans. Some occur naturally, such as volcanic ashes, pumicite, opaline cherts, clays, and shales. Natural pozzolans often need to be ground and clays and shales also need to be calcined for their pozzolanic properties to be maximized. Other pozzolans are synthetic, often industrial waste products, such as silica fume, fly ash, and quenched boiler slag

Specifications require a minimum concrete cover of 100 mm (4 in.) for concrete that is in direct exposure to sea water, 75 mm (3 in.) for coastal concrete, and 65 mm (2½ in.) for concrete that is exposed to deicing salts or on deck surfaces that are subject to tire stud or chain wear. The specification allows the minimum concrete cover over epoxy-coated reinforcement to be reduced to 40 mm (1½ in.).

Silica Fume — Silica fume is a highly effective pozzolan because of its high silica content, fine particle size, about 0.1 μm (3.9 x 10^{-6} in.), and large surface area. When silica fume is mixed into concrete, it reacts with excess calcium hydroxide to form calcium silicate hydrate binder, which causes the material to be stronger and less permeable. The small size of silica fume particles allows them to fill in voids in the cement paste and between the paste and the aggregate. As a result, concrete made with silica fume has a less permeable microstructure with fewer gaps or large calcium hydroxide crystals.

Blast-Furnace Slag — Blast-furnace slag is a by-product of the iron and steel industry. It is composed of lime, silica, and alumina, with smaller amounts of magnesia, alkali oxides, and iron oxides. The composition of slag is dependent upon the industrial process and the raw materials used, but must be at least 40% lime to be used as cement. To be effective as a cement, slag must be cooled rapidly because its physical structure depends on the rate of cooling. Slag is usually quenched, which forms a reactive glass.

Slag will not hydrate unless it is activated by the addition of other compounds, generally calcium hydroxide or calcium sulfate, which is most easily supplied by the hydration of portland cement.

Fly Ash — Fly ash is a byproduct of powdered coal burning. It is an inorganic residue that is trapped by electrostatic precipitators, mostly in coal-fueled power stations. Fly ash is a good pozzolan because it is already finely divided and, unlike most natural pozzolans, it is commonly in the form of tiny spheres, meaning that it can increase the workability of concrete without increasing the amount of water needed. Another reason that fly ash is popular is that it is readily available, especially near population centers, where a significant percentage concrete construction takes place.

Study- comparing the chloride resistance of concretes containing fly ash, silica fume, and ground granulated blastfurnace slag was performed. Mixes were designed with 65% slag, 30% fly ash, or 10% silica fume cement replacement, by mass.

The studies described in this section have identified a number of ways to increase the quality of concrete for bridge structures. These are some of the reoccurring conclusions:

- A minimum of 25 mm (1 ½ in.) concrete cover over the reinforcement should be used on all heavy structure like bridge.
- The w/c ratio of concrete to be used in reinforced concrete heavy structure should be kept below 0.40.
- Fly ash and blast furnace slag can reduce the permeability of concrete to chloride ions, but do not do so as effectively as silica fume.
- Silica fume can reduce the permeability of a concrete mix to chloride ions; however, the workability of the mix will be reduced, requiring a high-range water-reducer, and the use of proper construction and curing techniques is important to minimize plastic shrinkage cracking.
- The optimal amount of silica fume in silica fume concrete for heavy structure is 6 to 8% by weight of cement.

Cathodic protection

Cathodic protection is currently becoming one of the most useful methods in corrosion protection because it controls the electrochemical corrosion process itself. The critical areas of this multi-discipline technology with respect to system performance and future development are the anode system, anode overlays, and assessment of cathodic protection performance.

This preventive method is based on the use of a sacrificial anode which is consumed during corrosion and the reinforcement remains unaffected. The standard electrode potential of the sacrificial anode must be lower than the standard electrode potential of the reinforcement so that during galvanic corrosion, the reinforcement acts as the cathode and remains unattacked. Zinc.

sacrificial anode- is the unanimous choice for cathodic protection. This may be present in the form of a coating or separately, being electrically connected with the reinforcement has developed a technique based on the use of a zinc wire as sacrificial anode along the length of a rebar. He observed that the extent of galvanic protection of the steel and the galvanic corrosion rate of the zinc were functions of the concrete conductivity, overlay thickness, steel surface area, surface conditions, and other factors. Zinc may be applied (i) by hot dipping of the rebar in the molten zinc followed by chromatizing treatment to produce galvanized rebar (ii) by flame or arc spraying, known as sprayed-zinc sacrificial anodes.

Impressed Current Cathodic Protection- This system is more flexible but more complex than a galvanic anode system. The basic principle is the same for both systems, except that the impressed current system energizes the anode by means of an external electrical energy source. The DC current is passed into the electrolyte by

means of an internal electrode like a lead-silver alloy or platinum. It is found that this alkalinity is produced at the cathodically impressed rebar as the impressed current uses up the dissolved oxygen, requires the hydroxyl ions to carry the ionic current, and produces hydrogen.

For cathodic protection to work effectively, there must be a way for oxygen to diffuse to the cathodic area, so that it takes part in the cathodic reaction. The anodic area becomes acidic and the alkaline OR ions are moved away from the rebar as a requirement for continuous current flow.

V. METHODOLOGY

Damage which was attributed to corrosion of reinforcement the repair was divided into several activities which are briefly discussed below:-

- Surface preparation : The area where corrosion of reinforcement has external sign, the area was prepared by removing the loose concrete till sound concrete was reached. All the exposed reinforcement were suitably cleaned in order to free from rust. The exposed concrete surface was repeatedly washed with water spray.
- Anticorrosive treatment to reinforcement: Anti corrosive treatment was given to derusted reinforcement for an ideal protection against removed corrosion. For this purpose 2 coats of Sikatop armatec 108 was applied followed by curing for 24 hours.
- Bonding coat: The cleaned concrete surface was made totally saturated with clear water. Cement slurry modified with polymer emulsion sikalatex was brushed in to concrete surface as bond coat.
- Polymer mortar for inner layer: While the bond coat is still tacky, the filling of inner portion was done with polymer modified sikatop 122 and was well finished. Repaired mortal was cured for 2 days and the repair was allowed to dry.
- Carbonation resistant coating: In order to present ingress of moisture and carbon dioxide a coat of carbonation protective coating with pure acrylic based sealoflex was applied.

In water tank the visible damage consisted of cracking and sp ailing of concrete mainly in circumferential bracings, junction of bracing and columns and radial bracing connecting inner and outer column. The repair of corrosion affected water tank was done as per following steps

- The area was prepared by removing all dirt, dust and other foreign materials. Loose concrete were removed till the sound concrete was reached. All the exposed reinforcement were suitably cleaned in order to free from rust.
- Holes were drilled in order to fix nozzles.
- Nozzles were placed with Sikadur 31, epoxy based adhesive along the crack line with deep penetration at a standard centre to centre distance.
- The crack mouth were then chipped open and sealed along its entire length with Sikadur 31 adhesive. It was then cured for at least 6 hours before the actual injection was carried out.
- Flexible tubes were attached to the nozzle for injecting into the cracks. The other end of the flexible tube would be fixed to injection gun.
- To avoid any counter pressure and to ensure an open injection system, the pipes were blown through in

continuous sequence with compressed air starting from the bottom to the top and it was made sure that prepared injection system was interconnected and open.

- The gun with sikadur 52, water thin epoxy-based resin was then connected to the lowest injection pipe. Slow and even pressure was applied until such time as the injection mass oozed out of the pipe immediately above the one being used. The gun was withdrawn and flexible pipe was immediately bent and tied with binding wire. The same process was repeated starting from the next injection pipe till all the nozzles were used. Next day, the nozzles were cut off.

VI. CONLUSION

The most common corrosion protection method in the United States today is the use of epoxy-coated reinforcing steel. Although controversial in many areas, epoxy-coated reinforcement has performed well in many states, including Kansas, since it was introduced in the early 1970s.

Based on the economic analysis performed in this study, the use of epoxy-coated reinforcement alone is more cost-effective than building a bridge with black steel reinforcement and no other corrosion protection method, but there are other methods that now appear to be more cost-effective than either of these options. The more cost-effective corrosion protection options include epoxy-coated reinforcement in combination with another system such as a membrane, overlay, or corrosion inhibitor. The increase in the cost of a new deck with epoxy-coated steel over black steel reinforcement is very small, so even if it is not expected to improve the service life of a structure, epoxy-coated steel is a low cost backup to other corrosion protection methods.

Research on stainless steel reinforcement indicates that it may remain free of corrosion in chloride contaminated concrete for more than 75 years, but the relatively high cost of stainless steel has prohibited it from being used for entire structures. Rather, stainless steel reinforcement is usually limited to areas where contamination is expected to be the highest. The present value cost of a deck with solid stainless steel reinforcement does not vary with changes in the discount rate in this analysis because no repairs will be required during the 75 year economic life. At a low discount rate (2%), solid stainless steel reinforcement is a cost-effective option compared to other options, but at higher discount rates (4%+), the present value cost of a deck with solid stainless steel is significantly higher than that of an unprotected deck for the 75 year economic life considered in this study. Stainless steel clad reinforcement is much less expensive than solid stainless steel reinforcement. In fact, its in-place cost is not much more than that of epoxy-coated steel. The performance of stainless steel-clad reinforcement should be similar to that of solid stainless steel bars if the stainless steel coating is continuous and the black steel core, exposed at the bar ends, is covered so that it does not come into contact with the concrete pore solution. Assuming that a bridge deck, constructed using stainless steel-clad reinforcement with the ends well covered, does not require any repairs within its 75 year economic life, the present value of the cost of a bridge deck built with stainless steel-clad reinforcement is significantly lower than the present value for the cost of any other corrosion protection system.

Low permeability concrete and concrete overlays have been successful in delaying the penetration of chloride ions into bridge decks as long as cracking is kept to a minimum, generally through the use of proper curing techniques. Research has indicated that low-slump, silica fume, and latex-modified overlays have similar service lives, as long as they are constructed and cured properly. Of the three, low-slump overlays are the least expensive.

Many transportation agencies in the northeastern United States and Canada use waterproof membranes with asphalt overlays as the standard method for protecting bridge decks from corrosion. Agencies are divided on the effectiveness of membranes. Some do not like to place asphalt on bridge decks because it traps water and hides deterioration in the concrete deck beneath, but many researchers feel that membranes offer excellent protection if they are properly installed, and they have performed well in many areas. Spray-applied liquid methacrylate membranes are expected to prevent the ingress of water and chloride ions into bridge decks for up to 50 years. Hot rubberized asphalt membranes are expected to last for up to 40 years, and are the least expensive option, other than stainless steel-clad reinforcement, in the present value economic analysis. Once the chloride concentration in a bridge has exceeded the corrosion threshold, the only way to prevent the corrosion of bare steel may be through electrochemical methods.

Cathodic protection systems can be installed permanently on both bridge decks and substructure members. They have been successful at stopping corrosion, even in severely contaminated structures. However, these systems require regular maintenance, which can be expensive. Currently, the most common impressed-current anode in use for the cathodic protection of reinforced concrete bridge decks is the titanium mesh anode, used in conjunction with a concrete overlay. The system fills the need for a durable impressed-current cathodic protection anode for bridge decks and pilings.

Cathodic protection systems are the most expensive corrosion protection options for new bridge decks in the present value cost analysis. However, cathodic protection systems are often installed on bridges that would otherwise need to be replaced, an option that is not addressed in this study. If they can prevent a bridge from needing to be replaced, these systems could still be cost-effective.

Zinc mesh pile jacket anodes show promise as sacrificial anodes for the splash zone of bridge piles in marine environments. Zinc-hydrogel anodes can provide protection for substructure members in marine or inland environments, as long as water can be kept out of the system.

Cathodic protection can be applied effectively and safely to prestressed concrete bridge members. However, if the resistivity of the concrete is not uniform, it may be difficult to obtain sufficient protection at areas of high resistance without generating hydrogen in areas of low resistance. Cathodic protection is not recommended for prestressed concrete structures with highly variable resistivity, which is often caused by large variations in moisture content.

Electrochemical chloride extraction has been shown to remove a significant fraction of chloride ions from contaminated structures. The procedure is not yet used as a standard corrosion protection method because most agencies cannot afford to close down even part of a bridge deck for the 6 to 8 weeks required for the process. However, this method has the potential to be an effective tool in the corrosion protection arsenal.

Corrosion inhibitors have been shown to protect against corrosion in chloride contaminated concrete in laboratory tests, but information on their performance in the field is limited. Research has shown that the corrosion inhibitor calcium nitrite can extend the service life of concrete structures. Because calcium nitrite reduces corrosion by chemically reacting with the steel, the effectiveness of calcium nitrite is dependent on the ratio of chloride-to-nitrite ions, and calcium nitrite is used up over time as it protects the reinforcing steel. Organic inhibitors provide a physical barrier that limits the number of chloride ions that reach the surface of the steel reinforcement. Both types of corrosion inhibitor have the potential to be cost-effective, if they perform as well in the field as they have in the laboratory.

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