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INNOVATIVE CORROSION CONTROL PRACTICES TO PROVIDE LONG TERM DURABILITY OF CONCRETE STRUCTURES -A way forward.

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Abstract

Corrosion of reinforcing steel and other embedded metals is the leading cause of deterioration in concrete. When steel corrodes, the resulting rust occupies a greater volume than the steel. This expansion creates tensile stresses in the concrete, which can eventually cause cracking and spalling initiating from concrete cover. Steel corrodes because it is not a naturally occurring material. Rather, iron ore is smelted and refined to produce steel. The production steps that transform iron ore into steel add energy to the metal. Steel, like most metals except gold and platinum, is thermodynamically unstable under normal atmospheric conditions and will release energy and revert back to its natural and original state—iron oxide, or rust.

This process is called corrosion and for corrosion to occur, there must be at least two metals at different energy levels, an electrolyte, and a metallic connection.

In reinforced concrete, the rebar may have many separate areas at different energy levels. Concrete acts as the electrolyte, and the metallic connection is provided by wire ties, chair supports, or the rebar, pre-stressing cables itself. Corrosion is an electrochemical process involving the flow of charges (electrons and ions) when structure is moist.

Causes of concrete deterioration due to corrosion are discussed in the paper. The corrosion may be due to excessive permeability allowing ingress of chlorides and sulphates, abrasion/erosion, traffic, hydraulic pressure, fire/heat, volume changes, plastic and drying shrinkage cracking, loss of support, load impact etc. in/on reinforced concrete structures.

Key Words: High performance concrete, permeability, shrinkage cracking, shotcrete.

INTRODUCTION:

As per IS: 6461:Part 3 for RCC structures and IS: 6461: part 8 for Prestressed concrete structures, corrosion may be defined as: “Disintegration of concrete or reinforcement by electrolysis or chemical attack. Chemical reaction of during corrosion When Oxygen is present is given as under:

- $Fe = Fe^{++} + 2e$ at Anode (+)
- $\frac{1}{2} O_2 + H_2O + 2e = 2 OH^-$ at Cathode (-)
- $Fe^{++} + 2 OH^- = Fe(OH)_2$
- $4 Fe(OH)_2 + 2H_2O + O_2 = 4 Fe(OH)_3$
- $2 Fe(OH)_3 = Fe_2O_3 + 3 H_2O$

Chemical reaction during corrosion when Chloride (Cl^-) is present is described as under:

- $Fe(Cl)_2 + 2H_2O = Fe(OH)_2 + 2H^+ + 2 Cl^-$
- $Fe(Cl)_2 + Ca(OH)_2 = Fe(OH)_2 + Ca Cl_2$
- When Carbonic or other acid are present
- pH < 8 causes corrosion
- $CO_2 + H_2O = H_2CO_3$
- $H_2CO_3 + Ca(OH)_2 = Ca(CO)_3 + 2H_2O$

Lower W/C ratio (less than 0.45) , less cover (less than 25 mm) as per specified size of aggregates and for specified grade may prolong the life of structures at least upto 100 years. Consequently, carbon dioxide which is present in the environment after reacting with calcium hydroxide released after hydration of cement may reduce alkalinity/passivity in concrete. Major factors which may promote corrosion are listed below:

- Used rusted bars even without specified coating with cement slurry/suitable paints
- No proper cover, lap length/coupler, finish, curing, right temperature,
- Cracking during pre-stressing,
- More water content, No plasticizers
- Strength of cover block less that the specified strength
- More than 0.9 kg/cum chloride content in concrete

Therefore, to reduce rate of corrosion of RCC structures following aspects are to be looked into:

i) National/ International specification on reduction of corrosion rate, ASTM C-876-15 and ASTM B 117, IS Codes IS: 6461, IRC:SP:40 and others may be referred.

ii) Innovative techniques to minimise corrosion rate to make durable structures with improvement in low permeability, sufficient concrete cover, quality of cover concrete, compatibility of vibro-compaction with respect to slump of concrete, use of modern admixtures, glass fibres, ultra-high performance concrete, self-compacting concrete as per IRC:SP:70, shotcrete, use of RO Water in making pre-stressed concrete structures, protection of passive films/coating to resist ingress of chemical attack from acid rains etc., and

iii) Remedial measures such as use of silica fume and other mineral admixtures, coatings, composite cement, jacketing, stitching of concrete, use of fibre reinforced polymer plates, use of low viscosity epoxy to repair distressed concrete due to reduce rate of corrosion and thereby to increase life of the structures under different seismic conditions.

2. IMPOVEMENT IN CORROSION RESISTANCE DUE TO DURABILITY:

Durability and long-term performance are two important criteria for corrosion resistant concrete structures with respect to prevailing environmental and foundation/soil conditions. Durability can not be sacrificed to attain high strength alone, there is need to see high variation in environmental conditions and properties of soil lying below the foundation of concrete structures during its design life. Although, high ultimate strength is accompanied by a low W/C ratio, proper compaction, extra grinding of cement, proper removal of excess air by using needle/shutter vibrator, vacuum dewatering, autoclaving yet this is not, in itself, adequate to satisfy all durability-related requirements to make corrosion resistant structures.

All types of concrete must provide acceptable corrosion resistance which indirectly needs frost resistance, repeated heat resistance, sufficient fatigue life, adequate serviceability and long-term sustainability for concrete structures which are normally designed for 100 years under present foundation and environmental conditions except expansion joints, bearings and crash barriers which generally have life 25 years.

Concrete containing approved quality of mineral and chemical admixtures at low water/cement ratio having adequate workability i.e. high-performance concrete (HPC) or ultra-high-performance concrete using fibres is need of the day to protect embedded steel from corrosion and for long term durability of concrete.

HPC is being used in shotcrete for RCC structures with or without fibres where erection of form work is very difficult. HPC is being used in self-compacted concrete on RCC structures for repair of heavily reinforced concrete structures to protect from corrosion. Self-compacting concrete is also used for repair of those structures where pouring of concrete from single point is not possible and also at places where concreting with slip-form is the requirement for widening/repair.

Periodically monitoring, protecting, timely repairing of the concrete structures further extends the service life of the structures after protecting them from corrosion.

Good performance observed for offshore high-performance concrete structures/ dams in the regions near sea in India, where concrete of compressive strengths of 45 to 80 MPa has been used. For these structures, problems due to corrosion of embedded steel has not been reported so far, even after 20 years of the combined exposure to design loading and heavy mechanical loading under severe marine environment.

Good quality very fine particles of mineral admixtures along with super-plasticizer make the cement concrete extra durable with improved long-term performance of RCC structures because of least permeability (of air, water and chloride) due to very slow chemical reaction of HPC with harmful compounds present in the concrete.

3. CURRENT MATERIALS AND TECHNOLOGIES TO HAVE CORROSION RESISTANT RCC STRUCTURES

Materials: For soil foundation and other allied works, most important materials are sandy soil (IS:1498), sound mineral aggregates (IS:383), high strength blended cement (IS: 1489, IS:455), soil stabilizers (IS: 4332), silicon, polyurethane or poly-sulphide sealant (IRC:57, IRC:15, MORTH specification), TMT deformed steel bars (IS:1786), plain bars (IS:432), curing compound (IRC:15, MORTH Specification) etc.

High embankment (IRC:75), drainage layer, capping layer, subgrade, sub base, base course, wearing course for RCC roads (IRC:101/IRC:15/IRC:58) and box culvert (IRC:35 for span length upto 6 m), minor bridges (length of bridge 6m -60m), major bridges (length of bridge more than 60 m) IRC:112, causeways etc shall be appropriately designed and considered as per quality control norms and variation in dimension and profile mentioned in MORTH Specification on Roads and Bridge Works-2014 (Fifth Revision).

Further, latest version of IRC: 112 for RCC and pre-stressed concrete, IRC 37 for flexible pavement on deck slab, IRC: 15/IRC 58 for rigid pavement, and IRC:SP 65 "Guidelines for Design and Construction of Segmental Bridges for segmental bridge construction shall be followed. Shotcrete and self-compacted concrete shall conform to IS: 9012, IRC:SP: 62 and IRC:112. IRC: 78 for filter media and IRC Hill Road manual shall be followed for construction of RCC roads and structures in hills. For construction of RCC roads and structures in water logged areas, IRC:34 shall be followed. Materials and the design mixes required shall be checked for quality as per IS: 10262. Materials and machinery shall be selected based on the availability, latest norms and previous experience.

In case of alternate materials, the modern pozzolana available today is fly ash which is a by-product of burning finely ground coal in electricity generating power plants. First, fly ash was first used in Metro project in Delhi.

However, the pozzolana next in use is silica fume which is a by-product of the manufacture of silicon, ferro-silicon alloy, from quartz and wood/carbon at 2000^{O}C. Chemically, micro-silica is a mineral; composed of ultra-fine, amorphous glassy spheres of silicon dioxide (SiO_2) of sizes 0.1 microns – 0.15 micron like nanoparticles. The bulk density of silica fume is therefore 200- 400 kg/cu m, it is available in densified and slurry form. Silica fume shall be first tested for physical and chemical properties conforming to IS: 15388-2003 and IS: 456-2000. First bridge where silica fume has been used is JJ Fly over in India by M/S Gammon India, Rajouri Garden Bridge in Delhi by UP Bridge Corporation, next Bandra Worli Sea link in Maharashtra by MSRDC and in concrete roads at CRRI and Dhaula Kuan in Delhi where in some slabs steel fibre reinforced concrete along with mineral admixtures have been used. Performance till date after 20 years found satisfactory.

Granulated blast furnace slag (a pozzolana having potential reactivity which needs only activation with little quantity of any alkalis or alkaline compounds) is found to be performing well in blended cement used in structures and concrete roads. Currently, in concrete pile for foundation, Portland slag cement (IS:455) is being used.

Granulated slag is harder and fly ash is softer than clinker, so during inter-grinding, granulated slag may be ground at higher fineness than ordinary Portland clinker. However, in case of fly ash, reverse may be the case, fineness of fly ash may be more than the fineness of clinker after inter-grinding. Separate grinding may be preferred if required.

Fly ash content or slag content can be determined in blended cement by selective extraction method or selective sedimentation method. Generally, Portland cement gets dissolved in cold diluted hydrochloric acid and fly ash and slag are very rarely soluble which can be determined easily. In case of sedimentation method, generally Bromoform liquid is taken which has specific gravity of 2.8 which is more than fly ash but less than OPC. In case of slag density of slag (2.9) is very near to Portland cement (3.15), so there is a need to select some other liquid for separation of slag from cement by this method.

Colour of concrete looks to be white when good quality fly ash is added. First use of ground granulated slag in blended cement was in Vishakhapatnam Bridge in container yard. Surprisingly, extremely high strength high performance concrete is being used in making M 200 Grade concrete (compressive strength 2000 kg/cm^2 at 28 days) in Mumbai in Samsung Tower. The approximate mix proportion is given in Table 1:

Table 1; Mix Proportion of Very High Strength Durable Concrete

Material	**Amount in kg**	**Specific Gravity**	**Absolute Volume in cum**
Cement	780	3150	0.2476
Slag Fine	180	2900	0.0620
Silica Fume	180	2300	0.0783
Sand	370	2700	0.1370
Coarse aggregate 10 mm	816	2700	0.3022
Admixture	18	1210	0.0149
Water	158	1000	0.1580
Total	2502		1.0000

To check the accuracy of the mix, the absolute volume of each ingredients is calculated first by dividing dry mass (of each ingredient required for 1 cum) by specific gravity and by adding, absolute volume of each ingredients shall be 1 cum as shown in Table 1.

Currently polymeric fibres are being used in toll plaza pavement and steel fibres in manhole covers and making special type of test track for iron tyred vehicles for high impact resistance and high abrasion resistance. Abrasion index as per ASTM C-779 for heavy traffic shall be minimum 58 and low traffic 38 value is recommended. In case of polymeric fibres specific gravity being less than the specific gravity of concrete, aggregates and cement, so fibres come at top and reduces plastic shrinkage cracks and shines in dark (retro refractive) with light impact. Reverse is the case with steel fibres, specific gravity being more, so fibres settle down during compaction in workable concrete mixes.

While using blended cement, as the concrete mix being cohesive, extra precautions with regard to mixing, curing and compaction shall be taken. While compaction of concrete, needle vibrator (60/40/20 mm dia) shall be inserted inside the concrete first, touched

with steel bars and then on shuttering/formwork till uniform mix and colour is attained with least air inside the concrete as well on the surface. Binding wires shall be bent in the interior not at outer cover portion to avoid surface bubbles at concrete surface. Extra compaction may cause bleeding and segregation in the concrete. Further to avoid segregation, size of coarse aggregates shall be maximum 20 mm, concrete shall not be allowed to fall from a free height more than 1.5 m and suitable chemical admixture shall also be used.

4. FACTORS MAKING CORROSION RESISTANCE STRUCTURES

Following factors shall be reviewed during executing of RCC and prestressed concrete structures:

i) **Least Permeability**:

Permeability is the property that governs the rate of flow of a fluid into a porous solid. One of the major causes is high content of void/porosity (in cement past, aggregates, and concrete) which may lead to earlier failure of concrete structures due to fast corrosion. Air content in concrete shall not exceed more than 2.5 % and in reinforced concrete, any crack of width more than 0.3 mm under loaded conditions needs more attentions to protect from, water/acid rains causing chemical and physical processes of degradation.

ii) Abrasion Resistance:

For deterioration by surface wear, abrasion by dry attrition (wear on pavements and industrial floors by traffic) special attention shall be given to the quality of concrete surface. Compressive strength of concrete is directly proportional to abrasion resistance. Sometimes, in the industrial floors ironite/ iron powder/steel fibres or other additives are admixed in concrete to make the surface abrasion resistance.

iii) Erosion resistance:

Erosion means wear produced by abrasive action of fluids containing solid particles in suspension (canal lining, spillways and pipes). On the other hand, cavitation means loss of mass by formation of vapor bubbles and their subsequent collapse. One of the remedial measure may be to avoid laitance (a weak layer of cement and aggregate fines paste on a reinforced concrete surface) to minimize corrosion that is usually caused by an over wet or overworking the concrete mix or during repair.

iv) Precaution during execution in Freezing environment;

When water freezes, there is an expansion of about 9%, however, some of the water may migrate through the boundary, decreasing the hydraulic pressure which depends on permeability of the material. Under such situation, concrete shall be preserved at least for 7 days at temperature more than 2^0C and curing with water is generally avoided in freezing regions to achieve desired strength without cracks..

v) **High Performance Concrete:**

Good quality and durable concrete structures are life line for the community and are essential for the country's economic well-being. Further, heavy rains and floods are the most destructive calamity causing heavy loss to the life and property. Floods and rains are the most recurrent problem in most parts of the flood –prone areas and coastal regions. Solution for these problem is use of High Performance Concrete.

High performance concrete in concrete girders, segments, hydro power projects, nuclear thermal power reactors etc is being widely used. It is commonly observed that by the use of 5-10 percent silica fume by weight of cement, concrete flexural/compressive strength up to 40 percent is increased and consequently abrasion/corrosion resistance is also improved. As the major factor considered in the design is, the flexural/compressive strength of the concrete, high performance concrete may be considered basic material for corrosion resistant reinforced and prestressed concrete structures.

5. GENERAL DISCUSSIONS AND OBSERVATION AS PER FIELD EXPERIENCE

If structures designed and constructed as per approved drawings, materials, with quality norms are mostly durable and corrosion resistant. However, because of some environmental issues sharp rise in temperature or sharp fall in temperature, high wind speed, very low relative humidity, earth quake, landslides, over loading on the structures, weaker foundation or any un-natural loading may tend to create defects and corrosion in the structures later at faster rate. There are different methods for measuring corrosion rate in reinforced cement concrete (RCC) and prestressed concrete structures viz. chloride diffusion, current in micro ampre cm, loss of steel in mm per annum $X10^{-3}$.

Based on the field experience and some laboratory tests it has been observed in general as a typical case, that corrosion rate is inversely proportioned to W/C ratio in concrete (if W/C ratio is reduced say by about 50%, approximately 3-4 times corrosion rate as chloride diffusion is reduced for W/C ratio ranging 0.24- 0.6.). Type of cement also affects corrosion of concretes containing Pozzolana cement, Portland slag cement which have less corrosion rate (say 20-30% lesser than corrosion rate in concrete made with Ordinary Portland Cement as per IS: 269-2015). Further, as per new code on OPC, the maximum strength of cement sand mortar of 1:3 ratio shall not exceed by 15 MPa as mentioned in cement code IS: 269. This will further minimize variation in concrete strength as well.

In case of concreting under water, improper selection of the mix, materials and excessive honey combing in concrete or misalignment of piles etc may cause damage to the structures. IS: 383-2016 has been revised after 46 years, some of the clauses have been revised based on the present environmental and climatic conditions, the new specification may further help to have more durable RCC structures.

It is essentially first to critically evaluate the reasons of distress and then repair as per MORTH Specifications, IRC:SP:40 or IS: 456 to extend its durability and corrosion resistance. Generally, slag cement as per IS: 455 or blended cement using powdered slag as per IS: 12089 is being recommended for concreting under water or near coastal regions. Now-a-days slag and flyash are being processed to increase its reactivity for improvement in quality purpose.

To minimize honey combing, use of such mineral and chemical admixtures (IS: 9103) are being used to minimize air voids, increase in durability and for faster construction self-compacting concrete is in use. 1% air voids (inter connected) generally reduces 6% strength. Practice shall be a**void** the voids as maximum as possible.

Now concrete made with fly ash and silica fume along with fibes (IRC:SP:46) are being used for repair and maintenance of structures to make them best cost effective and further improving its durability. IRC:112 and CPWD has already issued guidelines (CDO/SE (RR)/Fly Ash (Main)/387 dated May 13,2004) for the use of fly ash Grade 1 (IS: 3812) in reinforced concrete structures.

Now, there are BIS Guidelines for the use of silica fume (IS: 15388) to be used in concrete structures and pavements. Besides this, Guidelines on High performance concrete/silica fume for Bridges/pavements is also published by IRC (IRCSP: 70 and IRC: SP: 114).

The major issues to be looked into with regard to corrosion resistance of concrete are:

i) proper selection of cement and grade of concrete,

ii) minimum silt in fine aggregates,

iii) use of poly carboxylic ether based admixtures (IS:9103),

iv) adequate lap length and cover,

v) staggering of laps (50%),

vi) use of couplers when dia of steel bars is more than 36 mm,

vii) use of TMT Fe 500 D (as per IS: 1786) bars without welding,

viii) timely sealing of cracks with low viscosity epoxy of width more than 0.3 mm

ix) repairing of honey combed area (looking like honey bee house) /jacketing with rich concrete (> M 50) after completely wetting the existing old concrete for atleast 24 hours,

x) sprinkle water @200 g/sq m on fresh concrete or cover with wet hessian cloth after 4-6 hours of laying in extreme summer and after 10-12 hours in winter (just before initial setting time of concrete i.e strength 3.5 MPa as penetration resistance as per IS: 8142),

xi) checking alignment and variation in dimensions as per approved drawings,

xii) adequate use of seismic stopper in transverse and longitudinal direction,

xiii) avoid pre-stressing of wet concrete segments,

xiv) adequate balance between the quantity of concrete and steel in designing structures,

xv) more curing in case of high strength concrete and concrete made with blended cement,

xvi) no vibration during hardening of concrete.

xvii) The life of normal designed concrete structure is normally 100 years and by adding 5-10 % silica fume (the basic material for increasing durability), it has been stated that life could be extended up to 500 years or so with smaller size section.

xvii) sodium hydroxide, sodium stannate, sodium citrate and calcium hydro oxide are good corrosion inhibitors with which the medium within concrete becomes alkaline of required alkalinity. Keeping these in mind, regarding grade of concrete higher the grade; lesser the corrosion rate. ~50% increase in grade, may cause approx. 25-50% less corrosion rate.

xviii) increasing the bar dia say two times, there are chances of getting about two times less corrosion) since increase in dia reduces surface area proportionately. However, the principle of spacing between steel bars as reinforcement shall be as per IS: 456. That is spacing shall be minimum 2.5 times the maximum size of aggregates for better compaction of concrete.

xix) Last but not the lease is the crack width, double the crack width, corrosion rate is increased by about 25%.

xx) all these values may differ on case to case basis. Actual relation may be found out using specified mix, using in specified structures and at specified environment and at specified time and temperature. These points may be adopted after proper verification. These may be considered for education/ academic point of views only.

CONCLUSION:

Proper design, curing, finishing, concrete cover, lap length, epoxy coated steel in marine environmental conditions, requirement of coupling/ welding and other workmanship requirement as per approved drawing marked with "Good for Construction" drawings/IRC:112/IS:456/ MORTH specification/standard drawings is the back bone for making durable reinforced or pre-stressed or post tensioned concrete structures which may not be corroded up-to its design life. If TMT bar is being welded it should have specified lap (10-25D) and carbon equivalent shall be less than 0.53 as per MORTH and IRC:112.

REFERENCES

Sl No.	IS/IRC Code No.	Title of the Code/Guidelines
1	IS: 456	Code of Practice for Plain and Reinforced Concrete (Fourth Revision)
2	IS: 516	Methods of Test for Strength of Concrete
3	IS: 3812	Specification for Fly ash for Use as Pozzolana and Admixture (First Revision) (Reaffirmed 1999)
4	IS: 9103	Specification for Admixtures for Concrete
5	IS: 10262	Recommended Guidelines for Concrete Mix Design
6	IS:269-15	Specification of Ordinary Portland Cement
7	IS:SP:23	Hand Book on Concrete Mixes (Based on Indian Standards)
8	IS:383-16	Specification of Natural Coarse and fine aggregates