Anti-Carbonation Coatings in Extreme Environment for Durable RC Structures

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Abstract -   **RC Structures in an extreme environment are subjected to severe exposure conditions. The corrosion of reinforcement which takes place is a complex electrochemical process due to the ingress of either moisture, chloride ions, CO_2 or ingress of combined deleterious substances though the porous concrete and accelerated with other catalyst factors such as mean temperature, relative humidity and wind pressure. Thereby deterioration of RC structures becomes very fast which need protection by suitable protective coating to increase their service lives. This paper focuses the suitability of providing an aliphatic Acrylic anti-carbonation coating for durability of RC structures in such extreme environment.**

Index Terms -- **Anti-carbonation coatings, Carbon dioxide diffusion, Deterioration, Service Life.**

I.   INTRODUCTION

Concrete structures deteriorate with time and deterioration is much faster in extreme environment associated with high humidity, chlorides and CO_2 in the atmosphere. Ingress of moistures and deleterious substances such as chloride ions, CO_2 and other chemicals take place through the pores of the concrete by the process of diffusion and initiates the corrosion of reinforcement and subsequently damaging the RC (Reinforced Concrete) structures. Protection of RC structures by a suitable protective coating is a well accepted method for increasing the service life in such extreme environment. Without a protective coating the degradation of RC structures become very fast for corrosion of embedded steel reinforcement. Infrastructure projects such as bridges, flyovers, underpass and parking garages are prone to ingress of CO_2. A dense compacted concrete with mineral and chemical admixtures with a low water cement ratio alone can not prevent such corrosion. Hence additional protection measures such as protective coating, corrosion inhibitors of calcium nitrite based for new structures and migrating corrosion inhibitor for old structures, and corrosion resistant steel or anti-corrosive painting of steel is quite often essential for increasing the durability and service life. The latest technology of cathodic protection is also more suitable for additional protection for structures such as bridges and flyovers.

II.   DEGRADATION DUE TO CARBONATION

Carbonation is a natural process where calcium hydroxide Ca $(OH)_2$ in the hydrated Portland cement paste combines with carbon dioxide (CO_2) in the presence of moisture and produces calcium carbonate in subsequent reactions as shown in the equations below:
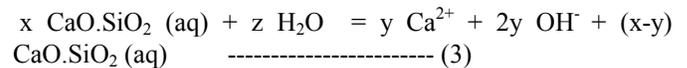
Dissolution of CO_2 in the pore solution of cement paste:

$$CO_2 + 2\ OH = CO_3^{2-} + H_2O \quad \text{-----------------} (1)$$

Dissolution of Ca $(OH)_2$:

$$Ca\ (OH)_2 = Ca^{2+} + 2\ OH^- \quad \text{---------------} (2)$$

Decomposition of hydrated silicate and aluminate phases, viz.:

$$x\ CaO.SiO_2\ (aq) + z\ H_2O = y\ Ca^{2+} + 2y\ OH^- + (x-y) CaO.SiO_2\ (aq) \quad \text{------------------------} (3)$$

Reaction to form Carbonate:

$$Ca^{2+} + CO_3^{2-} = Ca\ CO_3 \quad \text{----------------------} (4)$$

After breakdown of passivating layer around steel due to carbonation further requirements for corrosion is sufficient moisture to serve as low-resistance electrolyte and sufficient oxygen to support the cathodic corrosion reaction. Hence, the rate of carbonation is strongly influenced by the concrete strength, permeability, relative humidity, depth of concrete cover, moist curing period and exposure condition. A good impermeable concrete having more concrete cover protects against the ingress of CO_2. Due to formation of carbonic pore solution, there could be reduction of pH as low as 8.3 and consequently greater possibilities of enhanced reinforcement corrosion[1].When pH is less than 5 and the humidity is above 50%, an acid environment occurs which leads to extensive reinforcement corrosion. But when pH is in between 5.5 to 8.5 and humidity is above 50% at that time neutral environment reinforcement corrosion will begin which is moderate corrosion. But if the pH is over 8.5 and irrespective of any value of humidity an alkaline environment will occur where reinforcement is protected. Relative humidity plays an important role for diffusion of CO_2 through the concrete. Relative humidity lesser than 50% and higher than 80% does not affect much for CO_2 diffusion since the pores in the concrete become   either too dry or almost

saturated respectively thereby not creating any vapour pressure for the process of diffusion. The critical moisture content for carbonation of concrete was 80% as found out by Mmusi M.O et. al. [2]. Similarly the optimum climatic conditions for carbonation are relative humidity ranging between 50% and 70%, with wetting and drying cycles enhancing the reaction [3]. Talukdar et. al. have estimated the initiation of corrosion in Mumbai city will take place nine years sooner considering the factors affecting for the carbonation such as CO_2 concentration as 6%, the mean temperature as 30° C and the mean annual relative humidity as 74% [4]. Since the Mumbai is a costal city and having higher chloride concentration in the atmosphere the combined effects of chloride along with CO_2 was not considered in their study. However, in an extreme environment having combined deterioration due to carbonation and chloride, the rate of corrosion becomes very fast as shown in Fig.1.Thus corrosion of reinforcement is an extreme complex electrochemical reaction in which iron combines with oxygen to form iron oxides and iron hydroxides which are rust products. These rust products expand five to eight times as a result occupy more volume than uncorroded steel causing internal stresses due to confinement of corroding steel. These internal stresses results in cracking of concrete cover. After this initiation phase of corrosion, those cracks become source of further ingress for deleterious substances for propagating into larger cracks, delamination and spalling of concrete as shown in Fig. 2.

Fig.1. Corrosion due to combined action of carbonation and chloride ingress

Fig. 2. Corrosion of steel reinforcement due to carbonation in a bridge

III. METHOD OF MEASUREMENT OF CARBONATION

The various formulas and models have been used extensively by many researchers to find out the depth of the carbonation. Accelerated testing in carbonation chamber is used experimentally to verify the depth of carbonation of cured samples after simulating with certain variable factors which are responsible for accelerating the process of carbonation. Whereas the empirical formulas of carbonation given by Researchers Bre and Brown as shown in equations (5) and (6) respectively are more simplified to measure the depth of carbonation.

Bre's equation:

$$d = k \sqrt{t} \quad \text{--} \quad (5)$$

Where, d   is the depth of carbonation

     t   is the time of exposure

     k   is a coefficient.

The values of k which influences the rate of carbonation was found out in the research carried out by Moreno E.I. et. al., given as follows [5]:

    < 3 mm/year $^{1/2}$: Less

    3 mm – 6 mm /year $^{1/2}$: Moderate

    > 6 mm/year $^{1/2}$: Severe

Brown's equation:

$$d = k \quad (\sqrt{t}/S) \quad \text{------------------------------------} \quad (6)$$

Where, d, t and k as above and additionally S is the compressive strength of concrete

From the above equations 20 years carbonated depth (mm) for 28 days compressive strength of various grades of concrete are tabulated in Table 1 below:

TABLE I

ESTIMATED CARBONATED DEPTH

While designing any RC structures with a particular grade of concrete the carbonation depth is being calculated [6] with the above equations without any protective coating and cover depth is being provided accordingly taking consideration to the minimum cover depth as given in the codes of practices. This also helps for additional protection with a protective coating to decide the optimum cover depth while designing for the durability of the structures.

There is also evidence of increase in the compressive and tensile strengths, sometimes as much as 100% in the carbonated regime while testing with a rebound hammer. Because the carbonated concrete become very hard which may give a false reading if tested with a rebound hammer. A simple test of 1% phenolphthalein solution has to be sprayed to check the carbonation of concrete before one has to go for a rebound hammer test. If the concrete turns to white from pink after spraying then it is carbonated concrete, otherwise the concrete is non carbonated concrete.

IV. COATINGS AS CARBON DIOXIDE SCREENS

The method of measurement of carbon dioxide diffusion resistance of any coating can be as per ASTM E 96:2000, "Standard Test Method for Water Vapour transmission of Materials" which is basically for measuring water vapour permeability. However, the procedure developed by Robert Engielfried [7] can be used by exposing the coated surface to a CO_2 rich environment and thereby determining the CO_2 diffusion resistance based on mass gain of the sample.

The protective coating fills surface pores and bridges fine cracks & form a barrier to the movement of carbon dioxide. It is measured by carbon dioxide diffusion, which is defined as ability of the coating to resist the ingress of carbon dioxide and to stop the carbonation of the concrete. The CO_2 diffusion resistances (μ) are described in meters of equivalent air thickness. These values indicate how much more impermeable to CO_2 is the coating compared to air. Diffusion coefficient is typically around 7×10^{-8} cm^2/sec.

The equivalent air layer thickness (R) is the product of CO_2 diffusion coefficient (μ) and thickness of the coating (S).

$$R = \mu \times S \text{ meters} \quad \text{----------------------------------} \quad (7)$$

A value of R in excess of 50 m is normally considered to be adequate [8]. The R-value used in the design of coating system is to prevent the carbonation front reaching the steel

reinforcement in a 60 year life cycle, assuming the cover is not less than 25 mm otherwise, for less cover R values need to be increased. Also the R value remains same for old and new concrete of grade M 45 and above [8].

The other way of expressing carbon dioxide diffusion is equivalent thickness of concrete (S_c)

$$S_c = R/\mu \text{ concrete, -------------------------------- (8)}$$

Where, μ of concrete is taken as 400 which is an average value for concrete of strength 30N/mm^2.

S_c gives the equivalent concrete layer, which has the same resistance of CO_2 diffusion as the given thickness of coating. Typically, a high quality solvent based anti-carbonation system at 150 microns will have an equivalent concrete thickness of 700 mm. Hence for carbon diffusion a minimum thickness of 150mm is required.

V. ANTI-CARBONATION COATINGS

Anti-carbonation depends on barrier property of a coating and also coatings permeability or resistance to diffusion to atmospheric CO_2. Most of the anti-carbonation coatings are solvent based composition of acrylic solution polymer, properly selected & graded inert fillers, light fast pigments & additives. The properties of such anti-carbonation coating are given in Table 2.

TABLE II

PROPERTIES OF ANTI-CARBONATION COATINGS

The anti-carbonation coating is also formulated to protect reinforced concrete and other masonry cementitious substrate that is directly exposed to atmospheric conditions like UV radiation, high humidity, heavy rain, industrial pollution, & carbonation.It penetrates into the porous concrete substrate, producing an exterior masonry impermeable coating.
Various types of Silicone enhanced, vinyl and polyurethane coatings are also very much suitable for anti-carbonation properties. The coatings of generic base of polyethylene, epoxy, tar epoxy, chlorinated rubber, bituminous, cementitious, silicone and silicate are not suitable for anti carbonation coatings [8].

VI. METHOD OF APPLICATION

A. Surface Preparation for New concrete surfaces

New concrete / plastered surfaces must be allowed to cure for at least 6– 8 weeks before coating. Unless sufficient curing is done, entrapped moisture will exert pressure on the coating membrane. All surfaces must be clean, dry and free of loose material, oil grease; etc. Light grit blasting should be done in case of concrete surface ensures better cleaning & bonding. The concrete surface should be washed thoroughly with water to clean dirt & dust which may hamper decorative effect & bonding of the coating. Any previous growth of fungus & algae should be removed completely by vigorous wire brushing and cleaning with water. Treatment with proper biocide solution should also be done prior to the application to ensure complete removal of algae / fungal growth.

B. Surface Preparation for Previously Painted Surfaces

Alkyd paint if any should be sanded thoroughly to remove completely all loose particles. Mechanical methods are most suitable. Exterior surface previously coated with cement paint should be wire brushed and washed with water thoroughly and allowed to dry. Treatment for algae / fungal growth remains same as new concrete surface. All cracks should be treated appropriately using elastomeric sealant or crack repair materials.

C. Priming

To produce better bonding & surface finish, primer should be applied by brush or spray, diluting in 2:1 proportion with mineral turpentine. It should be allowed to dry for 2-3 hrs before application of finishing coat.

D. Finishing Coat

Two neat coats of anticarbonation coating should be applied without any dilution. It should be ensured that over coating is done when the first coat is dry for 5-6 hrs.

E. Precautions & Limitations

Although a gap of 5 – 6 hours may be given between the two coats, in cold / humid climates, dry up time may be extended. The coating products should be stirred well before the use. Application should not be done when ambient temperature is below 10° C.

F. Areas of Application

As anticarbonation, protective & decorative coating for bridges, flyovers, subways, underpass, parking garages, tunnels, chimneys, industrial structures, stadiums, and RCC water tanks. Also all concrete structures and cementitious exterior masonry plastered surfaces that are exposed to the extreme atmospheric conditions. Also all thin RCC structures having less cover such as facades, fins are other areas of application of anti-carbonation coating.

VII. FEATURES & BENEFITS

Carbonation – These coatings are excellent barrier to penetration & attack of carbon dioxide, water, sulphates and chloride ions.
Protection – The coating protects the structures from adverse marine and coastal environment.
Adhesion – They provide excellent adhesion to substrate, with a high film build-up.
Microorganism resistance – They also provide excellent algae / fungal resistance.
Ease of application – Since they are single component, straight way applied from the container, by brush, roller or spray application.
Durability – They provide a tough, flexible & durable coating.

VIII.   CONCLUSIONS

Anti-carbonation coating helps to provide a protective barrier to the concrete structures not only for carbonation but also to prevent the ingress of chlorides and moistures. Acrylic, silicone enhanced, epoxy and polyurethane are most suitable for such coatings. Considering extreme environment all the RC structures should be protected with an aliphatic acrylic coating to increase their service lives.

IX.   ACKNOWLEDGMENT

The corresponding author would like to give their sincere thanks to the Construction Chemical Division of Pidilite Industries Limited, Mumbai for using the product Dr. Fixit Concrete Guard, one pack acrylic anti-carbonation coating product and its product data sheet.

X.   REFERENCES

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