Effect of Supplementary Cementitious Materials on Corrosion of Reinforced Concrete-A Review

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Abstract -*The possible service life of the structure is significantly influenced by the safety and serviceability of a construction technique. A flexible and affordable building material, reinforced concrete often serves its original purpose effectively over the course of its service life. However, corrosion of the steel reinforcement is the most severe and expensive deterioration process impacting the reinforced concrete structures. Along with increased mechanical qualities, substituting other additives, such as extra cementitious materials, for the traditional, resource-intensive Portland cement can greatly minimize the danger of corrosion. These procedures increase the system's economic viability and sustainability. It is particularly effective to monitor various corrosion characteristics through a variety of procedures, including half-cell potential, the rapid chloride penetration test, electric resistivity, and diffusion coefficient. Concrete with mineral additives did not show active corrosion or depassivation of the reinforcing steel throughout the whole duration of attack by the chlorides.*

Key Words: Reinforced Concrete, Supplementary Materials, Mix Proportion, Mechanical Properties, Durability, Corrosion

1.INTRODUCTION

One of the most adaptable and often utilised materials in contemporary construction is reinforced concrete. Plain concrete is not suitable or cost-effective for many building structures because it is strong in compression but weak in tension. By bonding with the concrete, steel reinforcement overcomes this flaw and the two materials can work together to withstand applied tensile stresses. Concrete's resistance to shear and compressive pressures can be improved by adding steel reinforcement. Structures made of reinforced concrete are frequently intended to last more than 100 years. However, a lot of them fall short of this requirement for service life, particularly when RC systems are exposed to extremely hostile environments like marine or coastal situations. The planned service life of RC systems in a chloride-rich environment can be achieved either by increasing the concrete's resistance to chloride penetration or by shielding the reinforcing steel bars from the start of corrosion.

Corrosion of reinforcing steel embedded in concrete is an electrochemical process in which refined metal is converted into a more chemically stable form such as oxides, hydroxides, or sulphides . It is considered a major durability issue in concrete structures. In recent decades, Chloride-induced corrosion of steel bar is one of the severest and most urgent issues to marine structures, which will decrease concrete-reinforcement bonds and exfoliate the concrete cover.

2.CORROSION

Corrosion is referred to as the process of deterioration and consequent loss of solid metallic material, through an unwanted (or unintentional) chemical or electrochemical attack by its environment, starting at its surface. It requires an anode, a cathode, an electrolyte, and an electrical connection between the anode and cathode for the transfer of electrons. Coupled anodic and cathodic reactions take place on the surface of the reinforcing steel. Concrete pore water acts as the electrolyte and the body of reinforcement provides the electrical connection between the anode and cathode.[1] Normal reinforcement is very efficiently protected against corrosion when cast into a good quality alkaline and chloride-free concrete with a pH value in the range of 12.5 - 13.5. This is the well-known unique benefit of using reinforced concrete structures in building and construction. Such protection is due to the presence of a dense ferrous and ferric oxide layer (passive film) that prevents further oxidation of the rebar. The alkaline environment around the steel rebars protecting the steel is not always maintained and can be destroyed either by chloride attack or carbonation attack which reduces the pH of the pore solution.[2] The four basic mechanisms for transport of these aggressive ions include capillary suction, permeation, diffusion, and migration. The rate at which these ions penetrate to break down the passive film is a function of the quality and quantity of the concrete surrounding the reinforcement and the internal and external environments.

2.1 Chloride Induced Corrosion

The corrosion of steel reinforcement in concrete structures induced by chloride ion contamination is a major and dangerous problem than CO2-induced corrosion. Chloride induced corrosion of reinforcement, which usually takes place in marine environments or as a consequence of using de-icing salts or contaminated ingredients or chemical admixtures etc, can be studied in two separate phases. During the initiation phase, chloride ions propagating through the cover layer and reaching a critical concentration near steel. [3]Then, breaking down the passive layer around the bars which is otherwise stable in highly alkaline environments. This is followed by corrosion initiation and then propagation. During the propagation phase, corrosion starts, and rust products accumulating around the bars can lead to such structural damage as concrete spalling, delamination, loss of ductility of the bars, etc. While the reinforced concrete members can still sustain the applied loads during the 3 initial stages of the propagation phase, it is common practice and more conservative to limit the service life of the structure to the end of the initiation phase, i.e. the point when the reinforcement depassivates and corrosion starts. Several factors determine the duration of the initiation phase (i.e. the service life). This includes the rate of chloride ion diffusion, which is influenced by the permeability (physical absorption capacity) of the concrete/mortar and the chloride binding capacity of the matrix, as well as the stability of the passive film around the reinforcement, which is indirectly measured by the concentration of chloride ions required to break it down (chloride threshold). The volume of permeable voids plays an important role in chloride diffusivity, a more porous microstructure of concrete lead to a longer zig-zag path for the diffusion of chloride ion.

3. MINERAL ADDITIVES

To produce environmentally friendly concrete, it is inevitable for an alternative material to the expensive resource-consuming Portland cement. The incorporation of mineral additions originated from industrial waste materials such as silica fume, metakaolin, and fly ash, in replacing cementitious materials in the cement matrix can reduce the problem. [8] It has been promoted since it reduces pollutant waste and beneficial in construction works toward sustainable development. In special, these supplementary cementing materials can change physical characteristics of the cement matrix as its total porosity and the pore size distribution, thus interfering in transport properties such as permeability, capillary absorption, and ions 4 diffusion, which slows down the ingress of aggressive substances such as chlorides, sulphates, etc and changes electrical resistivity parameters [7]

4. RAW MATERIALS

Corrosion of steel reinforcement embedded in concrete is one of the major problems affecting the durability and sustainability of existing reinforced concrete (RC) structures. This can lead to a reduction in the load-carrying capacity of RC structures. Corrosion costs manifest in the form of premature deterioration or failure necessitating maintenance, repairs, and replacement of damaged parts. It can be a minimum of 3.5% of the nation's GDP. To avoid the risk of corrosion and enhance the service period of structures, it is necessary to modify the properties of steel and concrete.[1] In this respect, suitable concrete additives are effective to prevent corrosion on RC structures and lead to longer service lives and also a significant reduction in repair and maintenance cost. The use of supplementary cementitious materials makes the system a sustainable one.

4.1 Cement

Ordinary Portland cement is the most common type of cement generally used around the world, used as a basic ingredient of concrete. It is a fine powder produced by heating limestone and clay minerals in a kiln to produce clinker and adding 2-3% of Gypsum. [2] The most common type is Ordinary Portland cement. Ordinary Portland cement of 53 grades conforming to IS: 12269 is commonly used.

4.2 Supplementary Cementitious Materials

Fly ash is the finest of coal ash particles. It is the fine powder formed from the mineral matter in coal, consisting of the non-combustible matter in coal and a small amount of carbon that remains from incomplete combustion. Fly ash is generally light tan colour and consists mostly of silt-sized and clay-sized glassy spheres. Fly ash is a pozzolan, a substance containing aluminous and siliceous material that forms cement in the presence of water. When mixed with lime and water, fly ash forms a compound similar to Portland cement. [3] For more than a century, GGBFS was the primary additional cementing ingredient. It has pozzolanic and cementitious characteristics. The number of studies on the impact of GGBFS on the durability of various concrete and mortar types is excessive. The compressive strength of the mix is ultimately significantly increased by switching from PC to GGBFS.

4.3 Aggregates

Coarse aggregates in concrete occupy 35 to 70% of the volume of the concrete. The various properties of aggregates are maximum size, particle shape, textures and interior quality such as strength, density, porosity, hardness, elastic modulus, chemical and mineral composition etc. M-sand is crushed aggregates produced from hard granite stone which is cubically shaped with grounded edges, washed, and graded with consistency to be used as a substitute for river sand.[9]

4.4 Chemical Admixture

Super plasticizer is a chemical admixture to produce more workable and flow able mix using lower water content. The super plasticizer used in this research is Master Glenium SKY 8233. Master Glenium SKY 8233 is based on modified polycarboxylic ether. [4] The product has been primarily developed for applications in high performance concrete where the highest durability and performance is required. It is mostly compatible with all OPC, PPC, PSC and can be used with high pozzolanic material. It is a light brown liquid with relative density 1.08 at 25°C.

4.5 Water

Potable water can be used for casting purposes.

5. MIXING PROPORTION AND COMBINATIONS

Different concrete mixes with varying amounts of supplementary cementitious material will be prepared. Supplementary cementitious materials used are fly ash and metakaolin. From the literature, the optimum percentage of fly ash obtained is 25% replacement for cement mass. The optimum percentage of metakaolin obtained is 10% replacement for cement mass. For all these mixes tests for mechanical properties, durability properties, and corrosion properties were conducted.

6. ACCELERATED CHLORIDE INGRESS TECHNIQUE

Chlorides occur naturally in seawater at concentrations between 4 and 20 g/L and are also commonly present as sodium chloride used in de-icing salts. The ingress of chlorides is caused generally by three mechanisms: Absorption, permeation, and diffusion.[4] It is often the measurement of the coefficients of these transport mechanisms which are used to define the durability of concretes. The natural process of diffusion of chlorides in concrete is slow, so we adopt different techniques such as impressed voltage, wet/dry cycles, and saltwater immersion (3.5% NaCl).

6.1 Wet/Dry cycles (w/d)

The corrosion process was induced by wet-dry cycles in NaCl solution (NaCl diluted to 5% by mass or 0.855 M). The weekly cycles were 2 days of partial immersion of the specimen until 15 cm of its height in NaCl aggressive solution and subsequent drying during 5 days in a controlled environment (40oC of temperature and (50 ± 5) % of relative humidity). The NaCl solution was replaced every four cycles (28 days) to facilitate aeration sufficient level so that 26 the corrosion could develop. Specimens were subjected to a total of 8 cycles or 56 days of the attack in an aggressive solution containing chlorides.

7. MECHANICAL PROPERTIES

7.1 Compressive Strength

The test is done according to IS 516: 1959, by casting concrete cube specimens of mould size 150 x 150 x150 mm. The specimen shall be placed in the machine in such a manner that the load shall be applied to opposite sides of the cubes as cast, that is, not to the top and bottom. The load shall be applied without shock and increased continuously at a rate of approximately 14N/mm2 /min until the resistance of the specimen to the increasing load breaks down and no greater load can be sustained. The maximum load applied to the specimen shall then be recorded. The measured compressive strength of the specimen shall be calculated by dividing the maximum load applied to the specimen by the cross-sectional area of the specimen.

7.2 Split Tensile Strength

The test is conducted according to IS 5816: 1999. For testing cylinder specimens of size 150 mm in diameter and 300 mm long are taken after 28 days of curing. It is an indirect method of testing the tensile strength of concrete using a cylinder that splits across the vertical cylinder. The load shall be applied without shock and increased continuously at a nominal rate within the range of 1.2 N/ (mm^2/min) to 2.4 N/(mm^2/min). The maximum load applied shall then be recorded.

7.3 Flexural Strength

The test is conducted according to IS 516:1959. Flexure test evaluates the ability of unreinforced concrete beam or slab to withstand failure in bending. The results of the flexural test are expressed as Modulus of Rupture. In the present study, a two-point bending test is performed. The flexural strength is calculated by the equation as follows:
fb = $PL/BD2$

8. DURABILITY PROPERTIES

8.1 Water Absorption

The water cured concrete cubes (28 days) were then oven dried at 50 ±2ºC for 3 days until the mass became constant and again weighed. This weight was noted as the dry weight (W1) of the concrete cube. Specimens were kept in contact with water from one surface with water level not more than 5 mm above the base of specimen. [6]Flow of water from the peripheral surface is prevented by sealing it properly with non-absorbent coating for a specified time interval as per (ASTM C 1585) with their arrangement. Then this weight is noted as the wet weight (W2) of the concrete cube.

8.2 Sorptivity

The test was conducted to determine the measurement of water absorption rate on a reasonably homogenous material.

The sample was taken as the concrete specimen of 70±2mm dia. and 30±2mm thickness cored from 150 mm cube. After epoxy coating and curing, cut the cylinder into 30±2mm slices using a concrete cutting machine. Place the specimen in an oven at 50 C for 7 days and then cooled for 2 hours at laboratory temperature. After taking the initial weight place the sample on a plastic tray and pour Ca (OH)2 solution in such a way that 2mm of the 29 specimen should be submerged.[5] Weigh the specimen with a tie interval of 3,5,7,9,16,20 and 25 minutes.

8.3 Rapid Chloride Penetration Test (RCPT)

The test apparatus consists of 2 cells filled with 3%Nacl as cathode and 0.3 N NaOH as anode are connected to a power source. Then apply 60 V for 6 h to determine the permeability of the chloride ions in terms of the charge passed through the specimens. Take the measurements on the multimeter every 30 minutes and take the cumulative which will represent the charge passed through concrete. A large amount of charge passed indicates high chloride ion permeability which shows the poor quality of concrete. The test was conducted on concrete samples at ages 28, 56, 70, and 90 days. The sample should be sliced one with 100mm dia. and 50mm height.

9. CORROSION PROPERTIES

9.1 Electrical Resistivity

Surface resistivity (ρsr) measurement was performed by a commercially available 4-point Wenner probe surface resistivity meter at ages 28, 40, 56, 70, and 90 days. The device consists of four electrodes in a straight line and at equal distances of 3.8 mm. [7] The Alternative current induced from exterior probes to the concrete specimens and the resulting potential drop (V) is measured by the two inner probes and convert the potential drop to resistivity. Resistivity gives the direct measure of permeability or interconnectivity of pores. Thus, durable concrete has a higher resistivity. All measurements are started after calibrating the device.

9.2 Half Cell Potential

It is a non-destructive electrochemical method to find out the probability of corrosion tendency of rebar in the concrete. This technique directly measures the potential of rebar using a high impedance voltmeter.[9] One of the terminals of the voltmeter is connected to rebar in the concrete and the other to a copper/ copper sulphate reference cell with a porous sponge at the end. The sponge is guided to slide over the surface of the concrete and readings from the voltmeter are recorded.

9.3 Gravimetric Mass Loss

Gravimetric mass loss measurements were conducted on samples that had been already used for Tafel tests based on the ASTM G1–03 protocol. After splitting the samples, reinforcing bars were taken out and lightly brushed with a non-metallic bristle.[1] Then they were immersed for about 20 min in a chemical solution composed of 1000 mL hydrochloric acid (HCL, sp. gr 1.19), 20 g antimony trioxide (Sb_2O_3), and 50 g stannous chloride ($SnCl_2$). During the immersion, the cleaning solution was vigorously agitated, and the bars were removed from it alternatively, and lightly brushed to ease removing the solidly adhered corrosion products.[6] Only reagent-grade chemicals were used to prepare the cleaning solution. After treatment, all the bars were brushed again, rinsed, and dried and their masses were measured consequently. This process was repeated several times to obtain a plotted function of mass loss vs. the number of cycles for each bar; the mass loss corresponds to the point where the graph begins to plateau.[10]

10. CONCLUSIONS

The mechanical properties of concrete with mineral additives is better than control specimen. After wet/dry cycle all strength values will increases.

- This may be due to the fact that NaCl solution have compressive strength accelerating properties at early ages that cannot be sustained long term.
- As regards Half-cell technique, systems with mineral additives maintained lesser corrosion potential values
- During the entire period of attack by chlorides, concrete with mineral additions did not denote reinforcing steel depassivation and active corrosion.
- Durability properties of concrete with additives is better compared to that of control specimen.

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