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Reducing Deterioration and Corrosion of Reinforcements in Transportation Structures

Koorosh Gharehbaghi[1] and Amrit Sagoo[2]

[1,2]RMIT University, Melbourne, Australia
E-mail: [1]koorosh.gharehbaghi@rmit.edu.au, [2]amrit.sagoo@rmit.edu.au

Abstract—*Reinforced concrete is unique in that two materials, reinforcing steel and concrete (includes in-situ RC, precast, pre and post stressed) are used together to satisfy the structural integrity design requirements in terms of bending and torsion and allowing flexible design layouts. Many structures in built environment particular in Civil Engineering are built from reinforced concrete: bridges, viaducts, buildings, retaining walls, tunnels, tanks, conduits, airport runways etc. However, these structures are continuously being challenged by aggressive external environments and contamination which there are exposed to, such as salts, carbonation, polluted air and acid rain. Invariably, the structural integrity is compromised through rapid deterioration and allowing the concrete to break down, reinforcements to corrode and costs the operator huge amounts for rectification works and in many instances a complete replacement of the concrete structure. With this background, this paper undertakes a forensic investigation of failure of steel reinforcements particularly within the transportation structures.*

Keywords: *Reinforced Concrete (RC), Mechanical Properties, Transportation Structures*

1. INTRODUCTION

The structural integrity of concrete structure can be compromised in many ways such as fire, aggregate expansion, sea water effects, bacterial corrosion, calcium leaching, physical damage and chemical damage (from carbonation, chlorides, sulphates and distilled water). Depending on the nature of exposure, surface hairline cracking which allows water ingress through capillary action and through a process of continuous wetting and drying and temperature changes the surface fractures to increase in width and depth accelerating the deterioration with concrete becoming porous with aggregates becoming exposed. The water ingress promotes corrosion and expansion of steel reinforcements within the concrete. The corrosion of the reinforcements may induce mechanical stress which in-turn creates a migration pathway of extensive cracking resulting in structural failure. Numerous analytical and experimental studies have been carried out on crack initiation by corrosion product and the crack propagation through concrete.

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 steel but the increased use of deicing salts and the increased concentration of carbon dioxide in modern environments principally due to industrial pollution, has resulted in corrosion of the rebar becoming the primary cause of failure of this material. The scale of this problem has reached alarming proportions in various parts of the world. This is a significant implication for the Concrete Corrosion of the Civil Structures.

The use of good construction design practices such as adequate concrete cover depth, corrosion-inhibiting admixture, and low-permeability concrete alone will not abate the problem, because concrete has a tendency to crack inordinately. Even corrosion-inhibiting admixture for concrete would likely not be of use when the concrete cracked. This situation essentially leaves the reinforcing steel itself as the last line of defense against corrosion. For this very reason, the use of a barrier system on the reinforcing steel, such as epoxy coating or other organic or even other possible metallic coatings, is even more critical in abating this costly corrosion problem. It is likely that there may never be any organic coating that can hold up to the extreme combination of constant wetting and high temperature and high humidity that reinforcing steel is often exposed to in the marine environments. There are many examples of good practices such as using epoxy-coated steel bars being incorporated within the concrete. Even though the concrete may be subjected to constant wetting but the epoxy coating protects the steel bars and thereby, delay the initiation of corrosion.

2. DETERIORATION AND CORROSION OF REINFORCEMENTS IN CONCRETE

Vast network of transportation infrastructures as highways, rails, waterways, etc. are key contributors to economic growth and productivity of a region. In Australia, more than 70 per cent of domestic passengers travel between Australia using roads. This medium of transportation infrastructure is also the first and economic choice for freight transport. Statistic shows more than 75 per cent of non-bulk freight is transported via roads which are predicting to increase by 50 per cent by 2030 [2]. Followed by the pattern of population distribution along the south east coast of Australia, transportation infrastructures are centered at Adelaide, Melbourne, Sydney and Brisbane. Reinforced concrete is the predominant construction materials in constructing many of these infrastructures around the world. It is a unique construction material which allows flexible design layouts and offers safe bending and torsion to satisfy design requirements. However, being exposed to harsh environment and contamination such as salts, acid rain, distilled water, carbonation, sulphur etc will be the reason for deterioration, results impacting performance of these structures significantly. Not to mention that deterioration of these structures is not only a safety issue but an economic issue as well. Failure of these structures could restrain transportation, results reducing economic benefits and gross domestic product (GDP).

There are few incidents where deterioration of concrete structures led to collapse the whole structure and causing human causalities. Two of such incidents happened to Point Pleasant (Silver) Bridge over the Ohio River in 1967 and the Mianus River Bridge on I-95 in Connecticut in 1983 due to corrosion cracks.

Deterioration of concrete infrastructures can be attributed to many factors from structural deficiency to corrosion of reinforcement and thermal expansion to fire damage. Corrosion is the most common reason of deterioration of reinforced concrete infrastructures around the world [3]. Steel reinforcement is added in reinforced concrete infrastructure to increase tensile strength while concrete provides compression. Generally, steel embedded in concrete structures does not corrode, however, due to insufficient cover, presence of large amount of chloride rusting may occur. The damages include cracking and spalling on concrete.

2.1 Mechanism of corrosion

Steel is made of iron-ore using significant amount of energy. Like most of the metals, steel is thermodynamically unstable and has a tendency to release energy and revert to original state of oxidized state which is known as corrosion. Corrosion in steel is an electrochemical process involving anodic and cathodic reactions. This process requires the presence of oxygen, electrolyte cells and electric potentials between metallic surfaces. In reinforcement subject to corrosion, electric cell is formed as cathodes and anodes. Electron current flows from anode to cathode; an active side of reinforcement act in this case as anode and loss electron which will travel to cathode and mix with water and oxygen from air. Ferrous ions (Fe^{2+}) will also move to concrete during this reaction. This anodic reaction can be represented as following:

$$\mathbf{2Fe \rightarrow 2Fe^{2+} + 4e^-}$$

The reaction at cathode commonly known as reduction reaction which produces hydroxides (OH^-) that combines with ferrous ions to form iron hydroxides.

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

$$2Fe+40H^- \rightarrow 2Fe(OH)_2$$

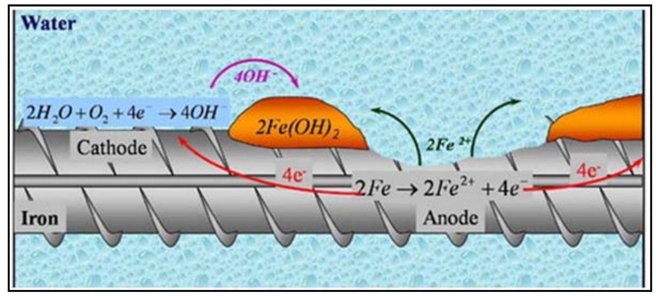

Fig. 1: Corrosion mechanism in reinforced concrete [14]

This iron hydroxide has the lower tendency of solubility and formed hematite (**Fe_2O_3**) if sufficient oxygen is available.

$$4Fe(OH)_2+O_2 \longrightarrow 2Fe_2O_3+4H_2O$$

On the other hand, if limited oxygen exists at the reinforcement, magnetite (**Fe_3O_4**) will be formed. In recent cast concrete which has a pH value of 13.5 [13], is an ideal alkaline condition for hematite and magnetite (act as a layer) to prevent corrosion due to their stable condition [4]. This layer is NOT the ordinary rust layer, and only a few nanometres in thickness [4], [1], [10]. When chlorides able to reach to reinforcement through penetration, ferrous ions will also react with chlorides besides reacting with hydroxyl ions.

$$Fe^{2+} + 2Cl^- \longrightarrow FeCl_2$$

This compound is highly soluble and can reach far from reinforcement, e.g. to concrete surface and oxidised to iron(III)(hydr)oxides [4]. In concrete, it exposes as red/brown color which indicates chloride induced corrosion. Carbonation (reduction of alkalinity by CO_2) is another reason to drop the pH value. When the pH value drops below 9.0, more and more iron atoms dissolve from passive layer and propagate corrosion.

3. TRANSPORTATION STRUCTURES

Given the importance of the costs associated with structures and a huge cost benefit analysis to users and the society. Hence it is extremely important that all possible methods applicable to controlling corrosion in existing concrete structures, especially bridges, be developed so that these structures do not fail prematurely [3]. Equally important is developing methods to avoid this costly corrosion problem in all new concrete Civil Structures to be constructed in the future. Given the very harsh service environments that many concrete Civil Structures are typically exposed to, it is difficult to build reinforced concrete structures that would be free of steel reinforcement corrosion [6].

The achievement of this goal requires the adoption of system approach, i.e., using a combination of different measures, such as adequate depth of concrete cover, quality concrete, corrosion inhibitors admixture, and corrosion-resistant reinforcements such as alternative reinforcements, corrosion inhibiting admixtures and son-on [9]. In achieving this, the proposed research has the following significant inarticulate the mechanical properties of Reinforced Concrete (RC) [11], [12]:-

1. Load Bearing Attributes (Strength and Durability). For Reinforced Concrete (RC) to be used as a component of highly used Civil Structure, its attribute for durability and strength need to be significantly tested under sever conditions. Michel et al. (2013) carried out tests that showed many possible problems in-particular with the ultimate usage and lower compressive strength. Furthermore, they also represented a correlation between fast polymerization process, and lack of the significant compressive strength. This clearly indicated that curing would possibly have an impact as a durability fact of the reinforced concrete.

2. Strength Characteristics. Pantazopoulou et al. (2001) research revealed that reinforced concrete for high demand including Civil Structures require ultimate and advanced strength behavioral properties compared to traditional non demand structures. However, during the Concrete corrosion compressive and flexural strength could significantly be affected. One aspect to increase the compressive strength is to increase the curing time. Pantazopoulou et al. (2001) also demonstrated that a longer curing time improved the polymerization process which increased compressive strength. Often increased workability gives the impression of a thinner consistency concrete which can reduce compressive strength, however with this 'new' additive to Reinforced Concrete (RC), the compressive strength remains relatively high. Generally in concrete composition, it is the steel (or synthetic fiber) reinforcement that contributes to the tensile strength while the concrete works in compression.

3. Durability Characteristics. For Reinforced Concrete (RC) to be used as a component of highly used Civil Structure, it requires significant durability mechanism. These greater engineering Properties include high compressive strength, greater resistance to acid attack and fire (up to 1320^{o}C) and low shrinkage creating a more durable product than ordinary concrete [5]. From the accessed data the testing in each of these areas is ongoing to continually improve the mixture; however initial results appear to be very promising. Tests show the For Reinforced Concrete (RC) is intrinsically highly resistant to acid attack due to the high degree of cross-linking present and the formation of an acid-resistant phase.

It is significant to add, that the above three mechanical properties need to be carefully considered as a part of any (Transportation Structures) treatments and therapies to extend the asset life.

4. CONCLUSION

Many Transportation structures are built from reinforced concrete: bridges, roads, airport runways and son-on. However, these structures are continuously being challenged by aggressive external environments and contamination which there are exposed to, such as salts, carbonation, polluted air and acid rain. Invariably, the structural integrity is compromised through rapid deterioration and allowing the concrete to break down, reinforcements to corrode and costs the operator huge amounts for rectification works and in many instances a complete replacement of the concrete structure.

Accordingly, this paper discussed the importance of steel reinforcements particularly within the transportation structures. In doing so, it is concluded that to effectively reduce d**ETERIORATION AND CORROSION OF REINFORCEMENTS IN TRANSPORTATION STRUCTURES, THREE IMPORTANT** mechanical properties of Reinforced Concrete (RC) needed to be cohesively investigated. These three mechanical properties include: Load Bearing Attributes (Strength and Durability), Strength Characteristics and Durability Characteristics. Investigating corrosion technicalities within these mechanical properties and thus providing appropriate treatments and therapies which will ensure that prolonged life of various transportation structures.

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