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Multi-Scale Influence of Severe Environmental Conditions and Material Characteristics on the Corrosion of Civil Engineering Reinforced Concrete Infrastructure and its Architectural Design Parameters

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Abstract: The durability of civil engineering reinforced concrete infrastructure is significantly dependent on corrosion protection. This calls for taking into consideration the detrimental effects of environmental stressors, material characteristics and the architectural design parameters. The environmental stressors consist of the severe conditions such as the presence of chloride ions, carbon dioxide, high temperature, acids, industrial pollutants, moisture, oxygen availability as well as the cyclic wetting drying exposures. All these severe environmental conditions cause corrosion initiation and propagation resulting in deterioration of the steel rebars embedded in concrete infrastructure. These environmental parameters act at various scales. The electro-chemical corrosion reactions take place at the nano and micro scale while the transportation of chloride and carbon dioxide takes into the pores of concrete take place at the micro scale. Cracking, spalling, delamination etc. causing loss of structural integrity happens at the macro level. Material related factors include cement chemistry, concrete mix design, its permeability, tortuosity of pores, pore structure, steel composition, surface condition etc. All these parameters and the performance of the protective systems developed perform a major role in corrosion mitigation and its kinetics. Parallel to these factors, the architectural and structural design also plays a vital role in corrosion control. These design parameters include member geometry, detailing quality, efficiency of drainage, ventilation considerations, quality of detailing, surface protection strategies and classification of exposure conditions. Overall, it is important to carry out an integrated interdisciplinary approach at the multi-scale level that connects the environmental exposure conditions with material characteristics under a durability oriented architectural design to protect the infrastructure from corrosion.

Key words: Environmental conditions; material characteristics; corrosion; civil engineering; reinforced concrete; architectural design.

1. Introduction

Reinforced concrete (RC) infrastructure is considered the backbone of modern human civilization as it supports the vital human utilities. This includes residential and commercial buildings, industrial facilities, transportation networks, coastal structures etc. Although RC structures are widely adopted due to their proven advantages, they remain vulnerable to one of the most detrimental degradation mechanism, corrosion of steel rebars embedded in concrete [1]. Corrosion not only threatens the structural integrity of civil engineering infrastructure but also reduces the service life and increases the maintenance cost. Thus, poses risk to the users as well as the surrounding communities. The recent past has seen phenomenal increase in the threat of corrosion due to increasing severity of environmental conditions. This has happened due to the rapid urbanization, industrial waste and pollution as well as the climate change. Hot weather [2], increase in humidity levels [3], threshold chloride [4] and wetting-drying cyclic effects from marine environment [5], the acid rain, carbonation [6] from atmospheric CO_2 have all contributed to the

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elevated corrosion levels. Such environmental conditions do not act as stand alone. Rather they couple [7] with the material variables [8] and architectural design parameters resulting in complex mechanisms which are not easy to predict and mitigate at various scales. This article presents the multi-scale [9] corrosion of steel reinforced concrete focusing on the connected roles of severity in the environment, materials engineering and the architectural designs. The need of the hour is to integrate various fields together combining civil engineering, architectural planning, electro-chemistry [10], structural engineering, durability design and concrete technology for proper corrosion management of civil infrastructure under the extreme environmental conditions [11].

2. Multi-Scale Corrosion of RC Infrastructures

Corrosion of steel rebars embedded in concrete is a multi-scale process. It spans from the atomic level electro-chemical reactions to the development of the oxides of iron ultimately resulting in the macro scale deterioration and cracking of civil engineering infrastructure [12]. It is important to understand these nano, micro and macro scale mechanisms to effectively prevent, monitor and control the corrosion. At the nano-scale, corrosion starts through the electro-chemical reactions at the interface of steel rebar and concrete. Corrosion of rebar is in general protected by the passive protective layer [13-14] developed under the alkaline conditions of concrete pore solution [14]. However, this protection is broken when the aggressive agents such as chlorides and CO_2 enter the concrete and react with the passive layer. At this scale these harmful agents attack the protective film by pitting [15] and uniform corrosion [16]. Pitting corrosion is dangerous at the localized points due to its concentrated nature. While the uniform corrosion is detrimental on the overall rebar surface. At the micro-scale, features such as saturation of pores, their tortuosity and connectivity [17] and the interfacial transition zone [18] control the transport of moisture, oxygen [19] and ions towards the rebar surface. Even slight variations in these parameters can collectively produce significant change in the initiation time and rate of corrosion.

Moving forward from nano and micro to macro scale, the above results in the formation of different oxides of iron which occupy much larger volume than the original steel rebar resulting in cracking and weakening/loss of bond along the rebar concrete interface at the meso scale. This increases the permeability of concrete which results in even more ingress of harmful materials resulting in increased corrosion rates and the cycle continues. The cracks keep on increasing in length and width until visible mechanical damage appears on the surface of concrete making it structurally and architecturally vulnerable.

Last and final stage of deterioration is the macro-scale destruction. At this stage the concrete starts spalling and delaminating. There is visible reduction in the cross-sectional area of steel reinforcement bars. This results in the reduction of load carrying capacity of civil infrastructure. Compromise occurs in the ductility, structural stiffness and earthquake performance of RC structures. From architectural point of view, visible loss happens in the functionality and usage of the structures, aesthetic quality and user confidence. The macro-scale damage often requires expensive repair and rehabilitation or even early demolition. This shows the importance of corrosion resistant design of RC civil infrastructure.

3. Effect of Severe Environmental Stressors

3.1 Chloride-induced Corrosion

Severe environmental conditions are one of the most influential parameter that determines the corrosion behavior of RC structures. These stressors can accelerate material degradation in both steel and concrete at all scales. Chloride ions [20] are one of the most detrimental agent occurring either in the ingredients of concrete or penetrate through the marine environment and from the de-icing salts. Coastal regions and marine environments expose the civil infrastructure to high concentrations of sodium chloride salt which is the source of chloride ions causing breakage of passive layer. Source of these chloride ions is the airborne salts, sea spray and the sea water. These chloride ions penetrate the concrete surface through the capillary pores and their suction, diffusion and permeation ultimately reaching the steel rebar surface and initiating the corrosion reaction [21]. Marine environments are most prone to corrosion due to the coupled effects of high humidity, wetting drying cycles and temperature variations. The tidal and splash zones show the highest corrosion rates. This makes the civil engineering infrastructure in the category of offshore platforms, bridges, ports and coastal buildings most prone to corrosion damage.

3.2 Carbonation-induced Corrosion

Carbonation induced corrosion [22] occurs when CO_2 from the atmosphere enters the concrete surface and reacts with the calcium hydroxide. This reduces the pH of concrete pore solution making is less alkaline. Certain range of alkalinity is necessary for the stability of passive layer protecting the rebar from corrosion. When the depth of carbonation reaches the steel rebar surface level, corrosion initiates in a uniform manner throughout the surface of rebar. Industrial environments and rapid urbanization increase the amount of carbon dioxide in the atmosphere making the carbonation process faster and easier to reach the rebar earlier. The architectural elements that have thin concrete cover and high surface area are more prone to carbonation.

3.3 Effect of Hot Weather, Climate Change and High Temperature

High temperature increases the rate of corrosion reaction. Increase in temperature reduces the chloride threshold value making it possible for corrosion to initiate earlier [23]. Increase in temperature also effects the activation energy of corrosion reaction [24]. It has been observed that the corrosion rate increases non-linearly and logarithmically with the increase in temperature and follows the Arrhenius law [25]. High temperature also induces thermal stresses which cause cracking. Gulf region coastal areas having hot weather and high humidity [26] are more prone to temperature-induced corrosion compared to relatively cooler and dry regions of the world. In contrast to the above, the colder regions offer reduced corrosion rates. However, they also induce freeze-thaw cycles in colder climates [27] which generate micro-cracks. These cracks provide a path for the entrance of harmful materials causing corrosion. Climate change causes corrosion fatigue and puts the reliability of steel reinforced concrete structures at stake [28].

3.4 Industrial and Acidic Environments, Pollutants, Wastes and Hazardous Materials

Industrial environments [29] produce emissions such as sulphur-dioxide, nitrogen-oxide and other harmful materials causing corrosion. Acid rain further contributes to the chemically aggressive environment. These environments deteriorate the reinforced concrete, reduce its alkalinity and increase the permeability of concrete pores. All this indirectly accelerates the corrosion. The corrosion of reinforced concrete is influenced heavily by exposure to pollutants, chemical waste and hazardous toxic materials. Under the effect of these materials, corrosion initiates earlier and progresses at a faster rate. These harmful materials degrade the cement hydration products. This results in increased permeability causing deleterious substances to enter the concrete. It also increases the ingress of moisture, aggressive ions and oxygen resulting in the breakdown of protective film on the rebar surface. In this context, the civil engineering infrastructure most likely to corrode faster includes contaminated industries, chemical plants, toxic construction sites and waste treatment facilities [30].

4. Effect of Steel and Concrete Material Characteristics on Corrosion

The composition, micro-structure and surface conditions of steel and concrete play a decisive role in the corrosion rate of RC structures. This depends on the concrete and steel material parameters. Concrete parameters include type of cement, quality of coarse and fine aggregate, nature of supplementary cementitious materials, concrete cover and w/c ratio [31]. These parameters influence the resistance to harmful materials by affecting the permeability and porosity of concrete. Porosity and permeability of construction materials are primary factors in durability performance [32]. Similarly, steel rebar characteristics [33] also play a vital role in determining the corrosion rate of RC structures. This depends on the chemical composition, surface condition [33] as well as the mechanical properties of the rebar. In addition to the conventional steel rebar, there are several other specialized types of rebars which can drastically control the corrosion rate. Galvanized rebars [34], epoxy coated rebars [35], micro-alloyed rebars [36] and stainless steel rebars [37] are among those specialized rebars. However, this specialization comes with a price and it is vital to keep a balance between the cost-benefit ratio, performance and buildability. Other construction materials that influence the corrosion of RC structures include surface coatings, sealers and corrosion inhibitors [38-40]. Inhibitors such as calcium nitrite [41] can delay the onset of corrosion initiation and mitigate the progress as well. While advanced nano modified coatings [42] provide multi-functional protection.

5. Architectural Design Parameters and Corrosion-Related Durability

The role of architectural design parameters [43-45] is often under-estimated for corrosion performance of RC structures. But this role is very crucial as it affects in several ways. The geometry and detailing are among the most important parameters in architectural design w.r.t the corrosion protection. This influences the drainage of structure, water retention and the exposure severity. Improper detailing for instance sharp edges and corners, poor slopes and trapped water features can lead to local corrosion at such spots. In addition to that the cover of concrete structure as well as the classification of exposure also matters a lot. The most effective barrier against corrosion is the provision of appropriate cover thickness. Architectural design that reduce the adequate cover thickness of concrete may compromise the corrosion durability. Similarly, the exposure classification during the architectural design stage must be in accordance with the severity of the environment rather than merely relying upon design code minimum requirements.

Other parameters that influence the corrosion rate w.r.t the architectural design are ventilation and proper moisture control. Adequate drainage system and ventilation protects the building from corrosion by avoiding moisture accumulation. Good architectural design promotes drying and increases the service life of civil engineering infrastructure. Furthermore, the aesthetic durability and the serviceability of the architectural design also mitigates corrosion. This can be done by avoiding corrosion induced stains, cracks and spalling of degraded architectural appearance. User perception is also a vital parameter in architectural design. Hence, the durability is also an important architectural design component and should be taken into account without fail.

6. Conclusions, Future Perceptions and Research Needs

Corrosion of steel reinforced concrete is a complex phenomenon. It happens at nano, micro, meso and macro scales. It is influenced by the severe environmental conditions, material characteristics and architectural design parameters. Tackling these challenges requires a shift from isolated to integrated approach considering all the above together in one single design. This can be achieved by multi-scale thinking and choosing performance based materials, taking into consideration the climate response as well as the civil engineering and architectural design parameters. This will result in a durable, sustainable, long life, corrosion resistant reinforced concrete infrastructure. In this era, corrosion control based design in not an option but a fundamental requirement of future civil engineering and architecture. The future research should focus on parameters such as smart corrosion monitoring and control systems, artificial intelligence driven prediction modeling techniques, severe environment resilient materials and synergy between the civil engineering and architectural innovations. Need of the hour is to create an interdisciplinary collaboration between civil engineers, architects and material scientists so that the challenge of corrosion in RC structures under changing environmental conditions can be dealt efficiently.

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