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## **Corrosion of Reinforcing Steel in Concrete Structures: Understanding the Mechanisms.**

By Jieying Zhang

Reinforced concrete is a widely used construction material for bridges, buildings, platforms and underground structures, such as tunnels and concrete pipes. The durability of a concrete structure is based on its capability to withstand a range of severe environments over long service life. Durable concrete structures can lead to sustainable buildings and infrastructure systems.

Despite the fact the majority of concrete structures showed good long-term performance and great durability, a large number of them are aging and present extensive degradation failure because of corrosion of steel reinforcement. The corrosion of steel reinforcement leads to concrete fracture through cracking, delamination and spalling of concrete cover, reduction of concrete and reinforcement cross sections, loss of bond between reinforcement and concrete and reduction in strength and ductility. As a result, the safety and serviceability of concrete structures is reduced.

For example, over 50 per cent of bridges in North America are made of reinforced or prestressed concrete, about 40 per cent of which have severe deterioration problems. Corrosion of steel is one of the main causes of this deterioration. According to a 2002 survey by research firms CC technologies and NACE International, the direct annual cost of metallic corrosion is between 3.1 and 4.5 per cent of gross domestic product (GDP) in the U.S., among which 16.4 per cent is from infrastructure, such as highway bridges.

In sound concrete, steel is protected from corrosion by a passive film that forms due to the high alkalinity of concrete pore solutions. They are saturated calcium hydroxide solutions containing small percentages of other alkali ions, such as sodium and potassium ions, which maintain a pH balance between 12.5 and 13.5. Under these pH levels, steel attains a high corrosion potential that leads to passivity – a condition of corrosion resistance for an active metal caused by the formation of a thin, surface film of corrosion products. The corrosion rate of passivated steel can be less than one micrometre per year. Carbonation of concrete or ingress of chlorides into concrete can, however, cause depassivation of the steel by damaging the integrity of the protective passive film. The degradation of passive film is more significant in the case of chloride ingress because it induces highly localized corrosion attack. Chlorides can come from either a marine environment or the wide use of de-icing salts during winter months. Active corrosion begins when the passive film starts to deteriorate. This accelerates the rate of corrosion and eventually leads to damage of concrete structures. Therefore, the durability of the passive film ultimately determines corrosion resistance and the performance of steel in concrete structures.

Although the conditions responsible for the corrosion of steel in concrete structures are well accepted, the depassivation and corrosion mechanisms are yet to be understood from a scientific point of view. Despite its importance, very little information is available on passive film and its deterioration mechanism. Passive film is believed to be about two and three nanometers thick and primarily composed of iron hydroxides. However, little is known about the chemical compositions – ferrous or ferric oxides – and the structure of the passive film itself.

While the role chlorides play in inducing corrosion is well understood (through competing with hydroxide ions, which stabilize the passive film), the adverse interactions between chlorides and the passive film are unclear. It is believed the chlorides disrupt the passive film, reduce the pH level of the pore solution or serve as a catalyst for oxidation. Empirical observations have found when chlorides reach a certain critical concentration, the passive film is damaged and corrosion is accelerated. This concentration is referred to as the chloride threshold concentration, an important indicator of steel corrosion resistance and performance used in standards and guidelines in the design of concrete structures in aggressive environments as well as a parameter to help predict service life. This limited understanding of passive film and the associated depassivation and corrosion mechanism is primarily due to the fact corrosion is a complex electrochemical reaction between steel and concrete, which is complicated further by environmental exposure conditions and the states of stress in the reinforcing steel under service or ultimate conditions. This makes it difficult to characterize corrosion, evidenced by the fact the chloride threshold value of steel measured by conventional electrochemical technique can vary greatly. While this technique measures corrosion on a macro scale, the growth and deterioration of passive film actually takes place on the nano-to-micro scales and is governed by the elemental compositions and nano-microstructure of the steel as well as the chemistry of the concrete pore solutions. To address this, nanotechnology can be used as a complementary tool to obtain a more precise characterization of passive film in terms of nano-microstructural material properties, such as how the alloys used in corrosion resistant steels enhance the performance of the passive film.

It is critical to apply both electrochemistry and nanotechnology to establish a quantitative relationship between the governing factors and the durability of passive film. This in turn will lead to better corrosion assessment, more precise characterization of corrosion resistance of steel and, eventually, better predict the service life and lifecycle performance of concrete structures.

Presently, the National Research Council Canada Institute for Research in Construction (NRC-IRC) is using both electrochemical techniques and advanced nanotechnologies to conduct research on: the growth and breakdown mechanisms of passive film in aggressive environments, particularly chloride-laden environments; the correlation between chemical composition and micro/nano structures of the steel substrate and its corrosion resistance; and the adaptation of advanced nano techniques, such as scanning electronic microscopy, atomic force micro-probing, ion micro-probing and in-situ tunnelling microscopy for applications in the surface analysis of corroding steel surfaces. Along with an improved understanding, the expected outcomes include an alternative and more reliable indicator of corrosion resistance for reinforcing steel and guidance to manufacture reinforcing steels that are corrosion resistant.

Dr. Jieying Zhang is an Associate Research Officer at NRC-IRC. Her research interests include corrosion of reinforcement in concrete structures, durability of concrete structures, microstructural characterization, non-destructive methods and analytical and mathematical modeling. Dr. Zhang got her PhD at University of California at Berkeley, and she is an adjunct professor in Department of Civil and Environmental Engineering of Carleton University and serves in Editorial Board of the International Journal of Concrete

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