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Effect of Corrosion on Reinforcement in Concrete: A Review Paper

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Abstract: Corrosion of reinforcement in concrete structures is a widespread issue that harms the durability and lifespan of infrastructure globally. It's a big challenge that shortens the expected lifespan of reinforced concrete. As the need for infrastructure to last longer, usually between 100 to 120 years, grows, along with the high costs of building and upkeep, fixing concrete structures becomes crucial. The main reason concrete deteriorates is because of carbonation and the corrosion of embedded metals like reinforcing steel. This paper reviews existing literature to understand the effects of corrosion better and presents a summary report to aid in addressing this problem effectively.
Keywords: Carbonation, Corrosion, Reinforcement, Chlorides, Sulphate, Steel, Iron Oxide.

I. INTRODUCTION

Corrosion in reinforced concrete structures poses a significant challenge to the durability and longevity of these essential infrastructures. Reinforced concrete is widely used in construction due to its affordability, versatility, and strength. However, its susceptibility to corrosion, primarily driven by the ingress of chloride ions, carbon dioxide, and other aggressive agents, undermines its structural integrity over time. When these corrosive agents penetrate the concrete cover and reach the embedded steel reinforcement, they initiate corrosion, leading to expansive rust formation. This process results in cracking, spalling, and degradation of the concrete, compromising the structural stability and safety of buildings, bridges, and other concrete structures. Corrosion-induced damage not only necessitates costly repairs and maintenance but also poses risks to public safety and the environment. Therefore, understanding, and mitigating corrosion in reinforced concrete is essential for ensuring the long-term performance and sustainability of civil infrastructure.

II. LITERATURE REVIEW

1) K. Lundgren (2007) This resource paper delves into the impact of corrosion on the bond between reinforcement and concrete in civil engineering structures. Through a combination of experimental studies and finite element analyses, the authors systematically investigate and describe the effects of corrosion on bonding. Notably, the study finds that both ribbed and smooth bars exhibit similar fundamental mechanisms during corrosion, but the magnitude of these mechanisms differs, influencing the overall behavior. The paper highlights that the bond capacity of smooth bars is generally lower than that of ribbed bars due to limitations in generating normal stresses at slip. Interestingly, corrosion, as long as it doesn't lead to cover cracking, can enhance the bond capacity of smooth bars to approximate levels of ribbed bars. The presence of transverse reinforcement is identified as a key mitigating factor, reducing the sensitivity of bond behavior to corrosion-induced splitting cracks. Conclusions drawn from the study include varying effects based on factors such as reinforcement type, transverse reinforcement, and concrete confinement. The review underscores the importance of transverse reinforcement in minimizing the impact of corrosion on bond behavior, presenting valuable insights for understanding phenomena and assessing existing structures in civil engineering applications.
2) Y. G. Du and L. A. Clark (2005) The experimental investigation delves into the impact of corrosion on the ductility of steel reinforcement, employing accelerated and simulated corrosion tests on both bare bars and bars embedded in concrete. The findings underscore the significant reduction in ductility due to corrosion, primarily attributed to the non-uniform distribution of cross-sections along the length of corroded bars. While the strength ratio, elastic modulus, and hardening strain remain relatively unaffected by corrosion, ultimate strain, ductile area, and elongation experience notable decreases. Notably, even a modest average corrosion level of about 10% can potentially diminish the ductility of embedded bars below minimum requirements for certain applications. Furthermore, the study suggests that while differences in ductility reduction between bar types and diameters exist, they are not statistically significant, emphasizing the overarching influence of corrosion level. Importantly, the paper highlights the necessity for engineers to comprehend the corrosion mechanisms and environmental

factors when utilizing laboratory or field data for predicting the response of corroded structures. Overall, the study provides valuable insights into the complex relationship between corrosion and reinforcement ductility, offering practical implications for structural assessment and design.

3) Luca Bertolini and Maddalena Carsana (2016) The keynote paper presents a comprehensive analysis of the durability challenges faced by reinforced concrete structures exposed to aggressive chloride-rich environments, such as marine or de-icing salt conditions. Through an exploration of the mechanism of chloride-induced corrosion of steel within concrete, the paper elucidates its detrimental impact on the service life of RC structures. These include investigations into the efficacy of corrosion-resistant stainless-steel bars and advancements in cathodic prevention techniques. By synthesizing findings from their research and those of other scholars, the paper underscores the limitations of conventional methods in mitigating chloride-induced corrosion, particularly in environments characterized by alternate wet and dry cycles with chloride exposure. Notably, the paper advocates for the use of additional preventative measures, such as stainless steel rebars or tailored cathodic prevention systems, to ensure the long-term durability of structures. It emphasizes the importance of selecting appropriate materials and implementing proactive maintenance strategies to extend the service life of reinforced concrete structures effectively. Overall, the paper offers valuable insights and practical solutions for addressing the challenges posed by chloride-induced corrosion in RC structures, thereby contributing to advancements in the field of concrete durability.
4) Deepak K. Kamde , Radhakrishna G Pillai (2022) They investigated the corrosion and bond characteristics of steel reinforcement with Cement - Polymer composite (CPC) coating which is widely used worldwide to prolong the initiation of corrosion. For corrosion studies, 20 lollipop Specimen with as received & Sandblast Steels, & with and without CPC coating were cast. They found that CPC as received coated steel had 50% less chlorides threshold than sandblasted CPC Coated steel. For bond studies, they used 16 pull-out specimens with CPC coated steel rebar cast. By that they found that even negligible corrosion can lead to ~ 50 to 70%. Experimental results show that the adequately applied CPC coating can result in premature initiation of corrosion.
5) Manote Sappakittipakorn and Nemkumar Banthia (2010) The research paper provides valuable insights into the impact of fiber reinforcement on the durability and corrosion resistance of concrete structures. By investigating the effects of cellulose and polypropylene fibers on chloride transport and corrosion initiation in reinforced concrete (RC) beams, the study sheds light on the complex interplay between material properties and environmental factors. The findings suggest that while fiber reinforcement may increase the overall diffusion of chlorides in concrete, it effectively binds with the chlorides, reducing the availability of free chlorides for steel corrosion. Moreover, the research highlights cellulose fiber's superior effectiveness in chloride binding compared to polypropylene fiber. The corrosion tests conducted over 56 weeks reveal that fiber reinforcement delays the onset of corrosion, yet its effectiveness diminishes under higher applied loads, indicating a threshold beyond which fibers become less effective. Overall, this paper underscores the potential of fiber reinforcement in enhancing the durability of concrete structures by mitigating corrosion risks, albeit with considerations for load levels.
6) Bulu Pradhan and B. Bhattacharjee (2009) The research paper presents a comprehensive investigation into the performance of reinforced concrete structures under chloride contamination, employing various electrochemical techniques for corrosion rate evaluation. By examining a wide range of specimens with different types of cement and steel, the study offers valuable insights into corrosion behavior and its correlation with influencing factors. The findings indicate that corrosion rate values obtained through linear polarization resistance (LPR) with guard ring arrangement closely align with gravimetric measurements, establishing LPR as a suitable non-destructive method for corrosion rate determination. Moreover, the study highlights the superior performance of blended cements like PPC and PSC over OPC in mitigating chloride-induced rebar corrosion, with Tempcore TMT steel exhibiting lower corrosion rates compared to Thermax and CTD steel. Furthermore, the analysis of variance underscores chloride content as the most influential factor on corrosion rate, followed by cement and steel types, with the corrosion rate remaining relatively constant over the testing period. Overall, this paper contributes significantly to the understanding of reinforced concrete durability and underscores the importance of employing electrochemical techniques for accurate corrosion assessment, providing valuable insights for enhancing the longevity of concrete structures in chloride-rich environments.
7) Ashutosh Shanker Trivedi and Sudhir Singh Bhadauria (2019) The research paper provides valuable insights into the corrosion behaviour of reinforced concrete structures exposed to concentrated sulphuric acid, addressing a significant durability concern in civil engineering. Through a meticulous experimental study employing a three-electrode electrochemical system, the authors observed the formation of a brown ring near the steel surface, leading to localized expansion and subsequent cracking of the concrete. The corrosion rate was notably high under immersion in concentrated sulphuric acid, emphasizing the severity of the

environmental exposure. Additionally, the investigation highlighted the influence of conductance on corrosion rate dynamics, with noteworthy distinctions between conditions with and without conductance. Interestingly, the study found the diameter of the steel bar to have a negligible impact on corrosion rate, contrary to conventional assumptions. Moreover, the observation of increased rusting near the top portion of the bar underscores the significance of proximity to the counter electrode and the absence of protective cover in this region. Overall, this research contributes valuable findings to the understanding of corrosion mechanisms in reinforced concrete structures, informing potential mitigation strategies and design considerations for enhancing durability in acidic environments.

8) Prasad V. Bahekar and Sangeeta S. Gadve (2019) The research paper presents a comprehensive investigation into the effectiveness of impressed current cathodic protection (ICCP) in reinforced concrete (RC) structures, particularly focusing on the use of carbon fiber-reinforced polymer (CFRP) as an external anode. By conducting experiments on large-scale flexural specimens, the study evaluates the optimum protection current density required to prevent rebar corrosion while maintaining or even restoring bond strength in CFRP-strengthened RC structures. The findings demonstrate that CFRP laminates can effectively serve as anodes in ICCP, eliminating the need for external anodes. Moreover, across varying levels of corrosion, all tested protection current densities successfully prevented rebar corrosion. Additionally, the study proposes a novel parameter, the ratio of percentage mass loss in rebar to load-carrying capacity of the beam, to determine the optimum protection current density that minimizes corrosion while maximizing flexural strength. The results suggest that a current density of 5 mA/m^2 is optimal for cathodic protection in CFRP-strengthened flexural members. However, it is noted that this proposed current density is specifically applicable to ICCP systems utilizing CFRP as an anode and may not be suitable for other types of anode systems. Furthermore, the study highlights potential challenges such as unintended contact between CFRP laminate and rebar leading to accelerated corrosion, and the degradation of the anode system with increased protection current density, despite reductions in mass loss. Overall, the research provides valuable insights into optimizing cathodic protection strategies for enhancing the durability and performance of CFRP-strengthened RC structures in corrosive environments.

9) Manu Harilal and Radhakrishna G. Pillai (2020) The research paper delves into the development of a novel ternary-blended reinforced concrete system, CFNI, aimed at reducing carbon footprints in cement production while enhancing corrosion resistance of embedded steel rebar. Through chemical and electrochemical tests conducted over 180 days in a simulated chloride environment, the performance of CFNI was compared with three other concrete systems. Results revealed a significant improvement in corrosion resistance in CFNI, attributed to its unique composition including fly ash, nano modifiers, and a corrosion inhibitor. Electrochemical measurements demonstrated a five-fold increase in polarization resistance compared to control concrete, indicating superior corrosion resistance. Additionally, CFNI exhibited lower chloride ingress rates and reduced apparent diffusion coefficients, indicating enhanced resistance against chloride attack. Microscopic analysis further corroborated these findings, revealing a lack of microcracks or pores at the concrete-steel interface in CFNI specimens. The study concludes that CFNI concrete shows promise in achieving long-term corrosion-free service life in aggressive chloride environments, with estimations suggesting initiation of corrosion is six times delayed compared to traditional OPC mixes. Overall, the research provides valuable insights into the potential of novel ternary-blended concrete compositions in addressing both environmental and durability challenges in the construction industry.

10) Sudha Uthaman and R.P. George (2019) The research paper presents a method to enhance the corrosion resistance of reinforcements by modifying fly ash concrete with nanoparticles. Through a combination of natural and accelerated corrosion tests, the corrosion resistance of four types of fly ash concrete specimens was evaluated, with and without nanoparticles. Electrochemical measurements revealed that reinforcements in nano-$CaCO_3$ modified fly ash concrete exhibited a noble potential value, high polarization resistance, and lower corrosion rate compared to other specimens. Impressed voltage tests supported these findings, showing longer crack initiation times and minimum anodic current in nano-$CaCO_3$ modified specimens. Additionally, the corrosion products of the cover concrete indicated a lesser presence of detrimental phases, suggesting improved corrosion resistance. The study also found that nano-$CaCO_3$ particles effectively plugged pores, reducing chloride ion penetration, and maintaining the passivity of the iron oxide layer around the steel rebar. Overall, the investigation provides valuable insights into the effectiveness of nano-phase modification in enhancing the corrosion resistance of fly ash concrete, offering potential applications in improving the durability of reinforced concrete structures in corrosive environments.

III. CONCLUSION

The above review paper concluded with,

1) Corrosion significantly impacts the bond between reinforcement and concrete, with smooth bars showing lower capacity compared to ribbed bars. However, corrosion can enhance smooth bar bonding if cover cracking is avoided.
2) Corrosion leads to a significant reduction in the ductility of steel reinforcement, emphasizing the importance of understanding corrosion mechanisms for structural assessment and design.
3) Cement-Polymer Composite (CPC) coatings can delay corrosion initiation, but even negligible corrosion can lead to significant bond strength reduction.
4) Fiber reinforcement delays corrosion in RC structure.
5) Nano-phase modification in fly ash concrete effectively enhances corrosion resistance, suggesting potential applications for improving the durability of reinforced concrete structures in corrosive environments.

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