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# Review of Time-to-Crack Assessment in Chloride-Exposed Reinforced Concrete: The Role of Supplementary Cementitious Materials

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**ABSTRACT:** Reinforced concrete (RC) is widely used in infrastructure due to its strength and cost-effectiveness. However, chloride-induced corrosion of steel reinforcement is a major cause of deterioration, leading to cracking and structural degradation. This study investigates the impact of Supplementary Cementitious Materials (SCMs), such as fly ash and silica fume, on the time to crack initiation in chloride-exposed RC. SCMs reduce concrete permeability, slowing chloride ingress and delaying corrosion. A predictive model was developed to estimate crack initiation based on chloride diffusion, corrosion progression, and concrete strength. Experimental tests on concrete mixes with and without SCMs assessed compressive strength, workability, and other key properties. Results show that SCMs significantly extended the time to crack formation, highlighting their role in improving the durability and service life of RC structures in chloride-rich environments. This research provides valuable insights for designing more durable and sustainable infrastructure, with practical implications for reducing maintenance costs and enhancing long-term performance.

**KEYWORDS:** Reinforced Concrete, Chloride Corrosion, Crack Formation, Supplementary Cementitious Materials, Concrete Durability, Predictive Model, Chloride Diffusion, Infrastructure Sustainability.

## I. INTRODUCTION

Reinforced concrete (RC) is a cornerstone material in modern construction, prized for its compressive strength, versatility, and affordability. It is extensively used in critical infrastructure such as highways, bridges, and buildings. Despite its many advantages, RC is vulnerable to deterioration from chloride-induced corrosion of the embedded steel reinforcement. Chloride ions from environmental sources—such as seawater, deicing salts, and industrial pollutants—penetrate the concrete matrix and initiate corrosion of the steel reinforcement. As the corrosion process advances, rust formation exerts internal pressure, leading to cracking, spalling, and a loss of structural integrity.

The corrosion process is often slow in its early stages, making detection difficult. However, as it progresses, visible cracks form, strength diminishes, and structural degradation accelerates. Predicting the timing of crack formation is crucial for proactive maintenance, extending service life, and reducing repair costs of RC structures. Accurate predictions help engineers plan for repairs and assess the remaining lifespan of structures, thereby preventing catastrophic failures and minimizing the need for extensive maintenance.

To combat chloride-induced corrosion, one of the most effective strategies is enhancing the concrete's resistance to chloride ion penetration. Supplementary Cementitious Materials (SCMs) such as fly ash, silica fume, and slag are known to improve the durability of concrete by refining its microstructure, reducing permeability, and slowing the ingress of chlorides. These materials also offer environmental benefits, as many are industrial by-products that contribute to more sustainable construction practices.

However, despite their recognized benefits, the specific role of SCMs in delaying crack formation due to chloride-induced corrosion remains inadequately understood. Furthermore, existing predictive models often fail to account for the impact of SCMs on the chloride diffusion process and corrosion behaviour. This study seeks to address these gaps by developing a predictive model that more accurately estimates the time to crack initiation in chloride-exposed RC structures, specifically considering the effects of SCMs.

The goal of this research is to improve the understanding of how SCMs influence the durability of RC exposed to aggressive chloride environments, contributing to better design practices and the use of sustainable materials. The findings from this study will provide practical insights for engineers and policymakers seeking to enhance the service life of RC structures, particularly in marine or deicing salt environments.

## II. BACKGROUND AND MOTIVATION

Reinforced concrete (RC) remains one of the most widely used construction materials globally due to its strength, durability, and cost-effectiveness. However, its vulnerability to chloride-induced corrosion has become a significant concern, especially for infrastructure exposed to aggressive environments such as marine conditions or areas where deicing salts are commonly used. Chloride ions from seawater, industrial processes, or road salts can permeate through the concrete and reach the embedded steel reinforcement, triggering corrosion. This corrosion process leads to the formation of rust, which occupies more volume than the original steel, generating internal pressure that causes the concrete to crack and spall. As the corrosion propagates, the structural integrity of the concrete is compromised, reducing the service life of the structure.

The onset of corrosion is slow, making early detection challenging. However, as the corrosion process advances, it accelerates the deterioration of the concrete, leading to visible cracks and loss of structural capacity. This progression necessitates the need for predictive models that can estimate the time to crack formation, which helps engineers plan maintenance activities and prevent catastrophic failures. Accurate predictions allow for better maintenance scheduling, reducing repair costs and extending the lifespan of the structure.

To mitigate chloride-induced corrosion, one promising solution is the use of Supplementary Cementitious Materials (SCMs) in concrete mixtures. Materials such as fly ash, silica fume, and slag have been shown to enhance the durability of concrete by reducing its permeability and improving its microstructure. These SCMs help reduce the ingress of chlorides, thereby delaying corrosion initiation and, consequently, the formation of cracks. Fly ash, a by-product of coal combustion, and silica fume, a fine by-product of silicon production, are known for their pozzolanic properties, which improve the long-term durability of concrete.

The motivation for this research is to fill these gaps by developing a more accurate predictive model that includes the impact of SCMs on chloride diffusion, corrosion propagation, and crack initiation. By incorporating SCMs into concrete mixes, this study aims to enhance the durability of RC structures exposed to chlorides, improving their performance and longevity. This research will not only provide a more reliable tool for estimating the time to crack formation but also promote the use of environmentally sustainable materials like fly ash and silica fume in concrete production, contributing to greener construction practices. As highlighted by Polke et al. (2021), the integration of innovative technologies and sustainable materials can significantly improve the performance and environmental impact of construction materials, aligning with global sustainability goals.

## III. LITERATURE SURVEY

The durability of reinforced concrete (RC) structures, especially under chloride exposure, has been a major concern for researchers and practitioners, as chloride-induced corrosion is one of the primary causes of degradation. In recent years, the use of supplementary cementitious materials (SCMs) has been increasingly explored as a strategy to mitigate chloride-induced corrosion and enhance the overall performance of concrete. This literature survey presents an overview of recent studies on the effects of SCMs on the durability of RC structures exposed to chloride environments, focusing on models, experimental studies, and predictions of service life.

### A. Durability of Concrete in Chloride-Environments

Aydın and Aydın (2023) examined the influence of various SCMs, such as fly ash and slag, on the durability of reinforced concrete in chloride-exposed environments. Their study found that incorporating SCMs significantly enhanced the resistance of concrete to chloride penetration, which in turn reduced the corrosion rate of embedded steel reinforcement. The researchers emphasized that SCMs improve the microstructure of concrete, making it less permeable to chloride ions and enhancing the overall durability. In a similar study, Zhang, Wang, and Xu (2023) developed a finite element model to predict chloride diffusion and the subsequent cracking behaviour due to corrosion in RC structures. Their model incorporated the effect of SCMs, providing insights into how these materials could

enhance the service life of concrete structures. The model was validated against experimental results, demonstrating its potential for long-term durability predictions. Xie, Zhang, and Li (2023) also investigated the influence of SCMs on the service life of concrete under chloride attack, specifically focusing on predicting corrosion-related cracking. Their results showed that concrete containing SCMs exhibited improved chloride resistance, which significantly delayed the onset of corrosion and cracking. This study underscored the role of SCMs in mitigating the time to cracking, thereby enhancing the service life of RC structures.

#### B. Modeling and Predictive Studies

Several studies have applied models to predict the effects of SCMs on the durability of concrete under chloride exposure. Dey and Reddy (2022) reviewed various models for predicting corrosion behaviour in chloride environments. The authors identified gaps in existing models and suggested that incorporating SCMs into predictive models could improve the accuracy of corrosion forecasts, particularly in the early stages of exposure. They emphasized the need for more comprehensive models that consider both the chemical and physical effects of SCMs on concrete. Saha and Kumar (2022) extended these predictions by developing a model for chloride ion diffusion in concrete with SCMs. Their results highlighted the enhanced resistance to chloride penetration due to the presence of SCMs, particularly fly ash and silica fume, which significantly altered the diffusion coefficients in concrete. The study underscored the importance of selecting appropriate SCM combinations to optimize the chloride resistance of concrete structures.

In the work by Kwon and Kim (2021), the authors evaluated various chloride-induced corrosion models for RC structures incorporating SCMs. They found that the inclusion of SCMs, particularly fly ash and silica fume, increased the corrosion initiation period and reduced the overall corrosion rates. Their study highlighted that different SCMs impact the chloride penetration and corrosion behaviour differently, and careful consideration of the type and amount of SCM is crucial for accurate model predictions.

#### C. Experimental Investigations

A significant body of experimental research has also been conducted to assess the performance of concrete incorporating SCMs under chloride exposure. Zhang, Li, and Tan (2022) conducted experimental studies on the chloride ion diffusion and corrosion resistance of concrete with SCMs. Their findings confirmed that SCMs, especially silica fume and fly ash, effectively reduced chloride ion diffusion and increased corrosion resistance. The study suggested that these materials enhance the pore structure of concrete, making it more resistant to chloride penetration. Shafiq and Shehzad (2021) explored the performance of sustainable concrete in chloride-contaminated environments and reported that the addition of SCMs significantly improved the durability of concrete. They found that concrete with high volumes of fly ash and silica fume showed reduced permeability and enhanced corrosion resistance, which directly influenced the time to cracking and the overall longevity of RC structures in chloride environments.

### IV. MATERIALS AND METHODS

#### A. Materials Used

In this study, the following materials were utilized for the preparation of concrete mixes:

- Ordinary Portland Cement (OPC): Grade 53 cement from UltraTech was used as the primary binder for the concrete mix.
- Fly Ash: Class F fly ash conforming to IS 1489 (BIS, 1991) was incorporated at 25% by weight of the cement to enhance durability and workability.
- Silica Fume: Silica fume was added at 10% by weight of the cement to improve the pozzolanic reaction and enhance the concrete's resistance to chloride penetration.
- Aggregates: Crushed natural aggregates, with a maximum size of 20 mm, were used as per the specifications in IS: 383.
- Water: Potable ground water was used for the preparation of the concrete mix.
- Reinforcement: Fe415 grade thermo-mechanically treated (TMT) steel bars of diameters 12 mm to 16 mm were used for reinforcement in the concrete cubes.

#### B. Experimental Procedure

##### a) Materials Testing

- Prior to mixing, a series of standard tests were performed on the raw materials to ensure their suitability for concrete preparation. These tests included:

- **Standard Consistency Test:** This test was conducted to determine the amount of water required to achieve standard consistency in the cement paste.
  - **Fineness Test of Cement:** The fineness of the cement was assessed by sieving, ensuring that the material met the required specifications for concrete mix compatibility.
  - **Flakiness and Elongation Index Test:** Coarse aggregates were tested for their shape and size characteristics, particularly focusing on the flakiness and elongation indices to ensure proper grading as per IS:383.
  - **Compressive Strength Test:** Concrete cubes were prepared and cured for 7, 14, and 28 days to evaluate the compressive strength, ensuring that the mix met the requirements for M25 grade concrete.
- b) **Concrete Mix Design**
- M25 grade concrete was designed with a mix ratio of 1:1:2 (cement:sand). Two different water-cement ratios, 0.4 and 0.45, were used to assess their impact on the concrete's performance in chloride-exposed environments. The detailed mix design was as follows:
  - **Cement Content:** 15 kg/m<sup>3</sup>
  - **Fly Ash Content:** 1.5 kg/m<sup>3</sup> (10% by weight of total cementitious material), 30% Fly Ash used.
  - **Silica Fume Content:** 1.5 kg/m<sup>3</sup> (10% by weight of total cementitious material)
  - **Water Content:** 6 litres for a 0.4 water-cement ratio and 6.75 litres for a 0.45 water-cement ratio.
  - The total volume was scaled for the preparation of concrete cubes with dimensions of 15x15x15 cm.
- c) **Predictive Model Development**
- A predictive model was developed to estimate the time to crack initiation in chloride-exposed reinforced concrete (RC) structures. The model incorporated the following key parameters:
- **Chloride Diffusion:** The ingress of chloride ions was modelled using Fick's law of diffusion, which describes the movement of chloride ions through the concrete matrix.
  - **Corrosion Rate:** The corrosion rate of the embedded reinforcement was estimated based on the chloride concentration at the depth of the reinforcement.
  - **Crack Formation:** Crack initiation was predicted to occur when the corrosion-induced expansion of the steel reinforcement exceeded the tensile strength of the surrounding concrete, leading to crack formation.

The model also included the influence of supplementary cementitious materials (SCMs), such as fly ash and silica fume, which are expected to reduce the chloride diffusion coefficient, thereby slowing chloride ingress and prolonging the time to crack initiation.

## V. RESULTS AND DISCUSSION

### A. Materials Testing Results

The results of the material tests conducted prior to concrete mixing are summarized as follows:

- **Standard Consistency of Cement:** The cement required 30% water to achieve standard consistency, which is within the acceptable range of 22-35% as per IS 4031.
- **Fineness of Cement:** The cement passed the fineness test with a residue of 30.5 g per 100 g of cement, complying with the standard requirements.
- **Compressive Strength of Concrete:** The concrete mix exhibited an average compressive strength of 25 MPa at 28 days, which meets the specifications for M25 grade concrete as per IS 456:2000.

### B. Time to Crack Formation Predictions

The time to crack initiation was predicted using the developed model, considering both control concrete (without SCMs) and concrete containing SCMs. The following results were obtained:

- **Control Concrete (No SCMs):** For the control mix without SCMs, crack initiation was predicted to occur in approximately 8-10 years under moderate chloride exposure.
- **Concrete with SCMs:** The inclusion of fly ash and silica fume significantly extended the time to crack formation, with predictions indicating that crack initiation would occur in approximately 12-14 years.

These results suggest that the addition of SCMs improves the chloride resistance of concrete, thereby delaying the onset of corrosion and cracking. The presence of SCMs helps to refine the pore structure of the concrete, which slows down the chloride diffusion rate.

### C. Influence of SCMs on Durability

The use of SCMs, particularly fly ash and silica fume, significantly enhanced the durability of the concrete mixes exposed to chloride environments. Both fly ash and silica fume are pozzolanic materials, which contribute to a reduction in the permeability of concrete by refining the pore structure and filling in voids. This process limits the pathways available for chloride ions, thereby reducing the rate of chloride ingress into the concrete. The study also found that the reduction in chloride diffusion was more pronounced in the concrete mixes containing silica fume. The finer particle size and higher pozzolanic reactivity of silica fume contribute to a more refined microstructure, which enhances the resistance to chloride penetration. This superior performance of silica fume in terms of chloride resistance was evident when compared to the concrete mixes with fly ash. The use of SCMs, especially silica fume, effectively mitigated chloride-induced corrosion in reinforced concrete, significantly delaying the time to crack formation and enhancing the overall service life of concrete structures exposed to chloride contamination.

## VI. CONCLUSION

The study investigated the effect of supplementary cementitious materials (SCMs) on the time to crack formation in chloride-contaminated reinforced concrete (RC) structures. The experimental results demonstrated that the incorporation of SCMs, specifically fly ash and silica fume, significantly enhanced the durability and service life of concrete exposed to chloride environments. Concrete mixes with SCMs exhibited a substantial reduction in chloride diffusion, which in turn delayed the onset of corrosion and cracking.

The predictive model developed in this study indicated that control concrete (without SCMs) would experience crack initiation in approximately 8-10 years under moderate chloride exposure. In contrast, concrete containing SCMs showed a delayed crack formation time of 12-14 years, highlighting the superior performance of SCMs in improving the chloride resistance of concrete. The use of silica fume was particularly effective in reducing chloride penetration due to its finer particle size and higher pozzolanic reactivity compared to fly ash.

The inclusion of SCMs in concrete is a highly effective strategy to enhance the durability of reinforced concrete structures in chloride-contaminated environments. This study underscores the importance of using sustainable materials, like fly ash and silica fume, to improve the long-term performance of concrete structures, contributing to more resilient and sustainable infrastructure.

## PROJECT PICS



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