Securing Concrete from Chemical Degradation caused by Chloride and Sulfuric Acid through Epoxy Coating

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***Abstract:** This investigation looks at the effectiveness of epoxy coatings in mitigating chemical degradation in concrete structures subjected to Sulphuric acid and chloride attacks. Concrete, a widely used construction material, is susceptible to deterioration in aggressive environments, which can significantly compromise its structural integrity and lifespan. This study specifically focuses on the impact of 0.35% sulphur and chloride solutions on the mechanical characteristics of M30 concrete, evaluating its flexural, compressive, and STSs over a 28-day period. Experimental results demonstrate that exposure to Sulphuric acid leads to a 16% reduction in CSt, a 23% decrease in flexural strength, and a 24% decline in split-tensile strength. Similarly, chloride exposure results in a 15% reduction in CSt, an 18% reduction in flexural strength, and a 25% reduction in STS after 28 days. However, the application of epoxy coatings on the chemically attacked specimens significantly enhances their mechanical performance. Specifically, epoxy treatment results in a 9% increase in compressive strength for sulphur-exposed specimens and a 12% increase for chloride-exposed specimens. Additionally, flexural strength improves by 19.1% and 10%, while an raises in split-tensile strength by 15% and 12% for sulphur and chloride attacks, respectively. The findings of this study underscore the critical role of epoxy coatings as a protective measure against chemical attacks, effectively restoring and enhancing the durability of concrete structures. This investigation contributes to the understanding of concrete performance in aggressive environments and highlights the importance of employing protective strategies to increase the concrete infrastructures' service life.*

***Keywords:** Concrete degradation, Epoxy coatings, Sulphuric acid, Chloride attack, Split-tensile strength, Flexural strength, Compressive strength, M30 concrete.*

1. Introduction

Among the most extensively utilised building materials in the world is concrete, celebrated for its versatility, strength, and durability [1]. However, despite its inherent resilience, concrete structures are not impervious to deterioration. Over time, various external factors, particularly chemical attacks, can compromise the integrity of concrete, leading to significant structural failures [2]. This issue is particularly pronounced in structures such as bridges, dams, and canals, which are frequently exposed to aggressive environmental conditions [3] [4]. Among the most common culprits of chemical degradation are Sulphuric acid and chlorides, both of which can initiate destructive reactions within the concrete matrix.

1.1 Chemical Attacks on Concrete

Concrete chemical attacks can be divided into extrinsic and intrinsic components [5]. Intrinsic factors involve the chemical composition and quality of the concrete mix, while extrinsic factors pertain to external environmental conditions that the concrete is subjected to throughout its service life [6]. Among the most critical external chemical attacks are:

Sulphuric Acid Attack: Sulphuric acid is particularly detrimental to concrete, when it interacts with the cement matrix's calcium hydroxide, leading to the formation of gypsum and ettringite [7] [8]. This reaction not only causes volume expansion, which can lead to cracking but also lowers the concrete's capacity to support loads. As a result, structures exposed to Sulphuric acid, such as wastewater treatment plants and industrial facilities, can experience rapid deterioration.

Chloride Attack: Chlorides, commonly found in de-icing salts and seawater, can penetrate concrete and initiate corrosion of steel reinforcements [9] [10]. This corrosion process generates expansive forces within the concrete, causing the concrete cover to spall and break. The ingress of chlorides is particularly problematic in structures located in marine environments or regions where de-icing salts are extensively used.

Alkali-Silica Reaction (ASR): Another chemical attack of concern is the alkali-silica reaction, where reactive silica in aggregates reacts with alkalis in the cement, leading to the formation of a gel that expands upon absorbing moisture [11]. This expansion can cause significant cracking and structural damage over time.

Carbonation: When calcium hydroxide in concrete combines with atmospheric carbon dioxide, calcium carbonate is created. This process is known as carbonation [12]. The concrete's pH may drop as a result of this process, which can further enhance the susceptibility of embedded steel to corrosion.

The consequences of these chemical attacks are profound, often leading to reduced mechanical properties, compromised durability, and ultimately, structural failure. Understanding the mechanisms behind these attacks is crucial to developing countermeasures that effectively mitigate their effects.

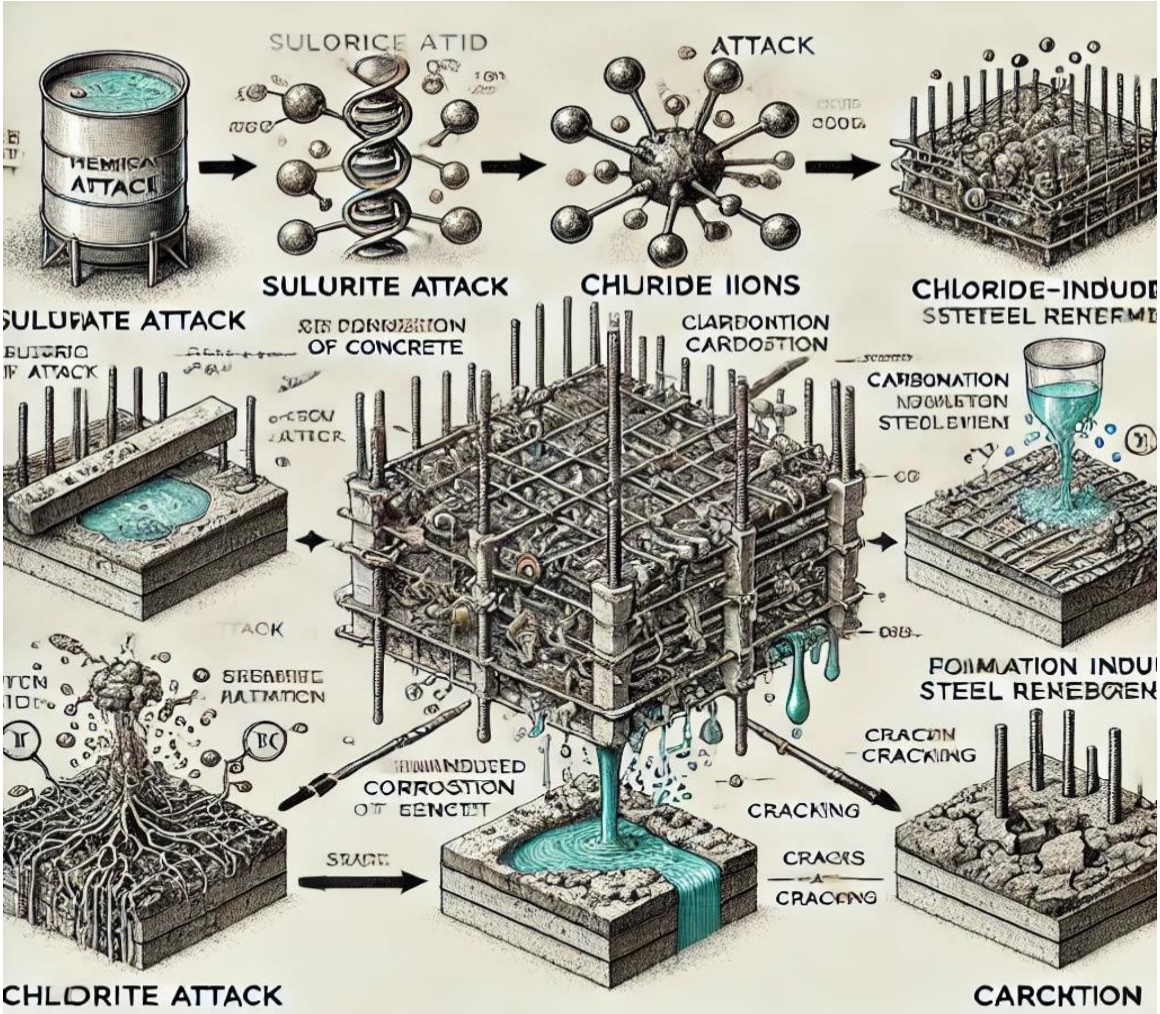

Figure 1: Chemical Attack Mechanism Diagram

1.2 Impact on Mechanical Properties

Concrete's mechanical characteristics, including its STS, flexural strength, and compressive strength, are crucial markers of its long-term stability. Chemical attacks can significantly impair these properties, leading to a decline in performance:

Compressive Strength: This characteristic assesses the concrete's resilience to axial loads. Research has shown that exposure to Sulphuric acid can reduce compressive strength by as much as 16% or more, depending on the concentration and duration of exposure. Similarly, chloride attacks can also lead to a reduction in CST, primarily due to corrosion-induced cracking.

Flexural Strength: Concrete's flexural strength is a measure of its resistance to bending forces. Studies indicate that Sulphuric acid exposure can reduce flexural strength by approximately 23%, severely compromising the concrete's performance in applications where bending stresses are prevalent.

Split-Tensile Strength: This property measures the tensile strength of concrete when subjected to axial tension. Chemical attacks can result in a notable decrease in STS, with reductions of 24% observed in sulphur-exposed concrete, affecting the material's ability to resist cracking.

The degradation of these mechanical properties not only poses risks to structural safety but also increases maintenance and repair costs, emphasizing the need for effective protective measures.

1.3 Mitigation Strategies: Epoxy Coatings

To combat the detrimental effects of chemical attacks, numerous mitigating techniques have been put forth and studied. One effective approach involves the use of epoxy coatings, which serve as a protective barrier against chemical ingress. Epoxy coatings are known for their excellent chemical resistance, adhesion, along with durability, making them an attractive option for protecting concrete surfaces.

Applications of epoxy coatings can [13-15]:

Seal the Surface: Epoxy coatings create a protective seal over the concrete, reducing permeability and preventing the penetration of harmful chemicals such as Sulphuric acid and chlorides.
Enhance Mechanical Properties: Studies have shown that epoxy-treated specimens can exhibit improved split-tensile strengths, flexural, and compressive, effectively restoring some of the mechanical properties lost due to chemical exposure.
Prevent Crack Propagation: By sealing existing cracks and preventing new ones from forming, epoxy coatings can help maintain the integrity of concrete structures over time.
Extend Service Life: Concrete structures' service lives can be greatly increased by applying epoxy coatings, which lowers the frequency and expense of repairs and maintenance.

1.4 Research Objectives

Ultimately, this project aims to determine how well epoxy coatings work to protect M30 concrete against the damaging effects of sulphuric acid and chloride attacks. Specifically, the study aims to:

1. Assess the impact of 0.35% sulphur and chloride exposure on the flexural, compressive, and STSs of concrete.
2. Investigate the performance of epoxy-coated concrete specimens in restoring strength after exposure to these chemical agents.
3. Analyse the long-term durability implications of using epoxy coatings as a protective measure for concrete structures.

This study attempts to shed light on the connection between chemical attacks and concrete performance while highlighting the potential of epoxy coatings as a viable solution to enhance durability in aggressive environments. The degradation brought on by chemical assaults on concrete structures presents a significant challenge in civil engineering. The results of this investigation should help with the understanding of concrete durability and inform best practices for protecting concrete in aggressive environments. By employing effective protective measures, such as epoxy coatings, it is possible to prolong the concrete constructions' useful life, ensuring their safety and functionality for years to come. The knowledge gained from this research will aid in developing more resilient concrete solutions and maintaining the integrity of critical infrastructure.

2. Methodology

The research techniques employed in this study are described in this section to assess the durability of M30 concrete structures subjected to chemical attacks from Sulphuric acid and chloride. The approach consists of material selection, experimental design, testing procedures, and data analysis.

2.1 Material Selection

The following materials were utilized in this research:
Concrete Mix: M30-grade concrete was chosen for its widespread application in construction. The concrete mix was designed with the following proportions:
Cement: Ordinary Portland Cement (OPC)
Aggregates: Coarse and fine aggregates conforming to IS standards
Water: Clean, potable water for mixing

Chemical Solutions: Two chemical agents were selected for the study:
Sulphuric Acid (H_2SO_4): A 0.35% solution was prepared for simulating sulphuric acid attack.
Chloride (NaCl): A 0.35% sodium chloride solution was prepared for assessing chloride-induced degradation.

Epoxy Coating: A commercially available epoxy resin was selected to evaluate its effectiveness in mitigating chemical attacks on concrete surfaces.

2.2 Experimental Design

The experimental design involved creating concrete specimens and exposing them to the selected chemical agents. The methodology included the following steps:

Specimen Preparation:
Concrete specimens were cast in standard Molds (150x 150 x 150 mm^3 for cubes and 100x100x500 mm^3 for beams) following standard mixing and curing procedures. The specimens were cured for 28 days in a controlled environment, maintaining optimal temperature and humidity levels.

Grouping of Specimens: Specimens were divided into four groups:

Control Group: Conventional M30 concrete without any chemical exposure.
Sulphuric Acid Group: M30 concrete exposed to 0.35% Sulphuric acid.
Chloride Group: M30 concrete exposed to 0.35% sodium chloride.
Epoxy Coated Group: M30 concrete specimens that underwent Sulphuric acid or chloride exposure followed by the application of epoxy coating.

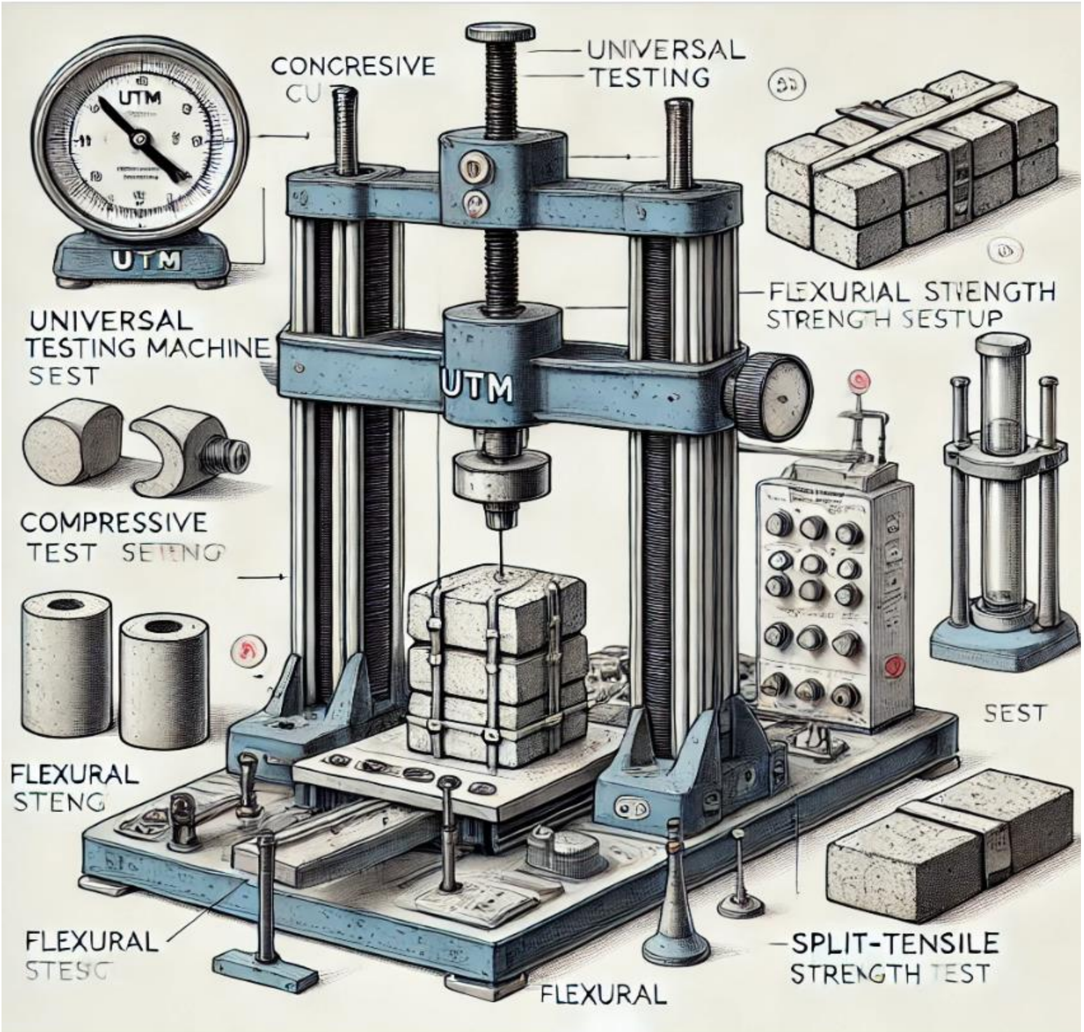

Figure 2: Experimental Setup Diagram

2.3 Testing Procedures

The following experiments were conducted to evaluate the concrete's mechanical properties:

Compressive Strength Test (CST):
This test was performed on 3 specimens from each group at 7, 14, along with 28 days of curing. The specimens were subjected to axial loading until failure using a UTM. The CSt was calculated using the following equations:

$$\textbf{Compressive Strength } (\mathrm{N/mm^2}) = \frac{\textbf{Load } (\mathbf{N})}{\boldsymbol{Area}\ (\boldsymbol{mm^2})}$$

Flexural Strength (FS) Test:
FS was assessed using a three-point loading test on beam specimens. The load was applied at the centre until failure, and the flexural strength was calculated using the formula:

$$\mathbf{FS\ (N/mm^2)} = \frac{3 \times \boldsymbol{Load}\ (\boldsymbol{N}) \times \boldsymbol{Length\ of\ the\ Span}\ (\boldsymbol{mm})}{2 \times \boldsymbol{Width}\ (\boldsymbol{mm}) \times \boldsymbol{Depth}\ (\boldsymbol{mm})2}$$

Split-Tensile Strength (STS) Test:

This test was performed on cylindrical specimens (150mm diameter and 300mm height) to determine the tensile strength. The specimens were loaded axially until failure, and the STS was calculated as follows:

$$\textbf{STS (N/mm}^2\textbf{)} = \frac{2 \times Load\ (N)}{\pi \times Diameter\ (mm) \times Length\ (mm)}$$

2.4 Data Analysis

Statistical Analysis: The results from the mechanical tests were compiled and statistically analysed to ascertain the importance of variations among the different groups. Comparative analysis was conducted between control specimens and those exposed to chemical attacks, as well as between chemically attacked specimens with and without epoxy coatings.

Graphical Representation: Results were visually represented through bar graphs and charts to illustrate the impact of chemical attacks and the effectiveness of epoxy coatings on the STSs, flexural, and compressive of concrete over time.

2.5 Conclusion

The methodology outlined in this research effectively assesses the durability of M30 concrete under chemical attacks and evaluates the protective capabilities of epoxy coatings. By systematically analysing the mechanical properties of concrete exposed to Sulphuric acid and chloride, the study aims to contribute valuable insights into enhancing concrete durability and performance in aggressive environments. The outcomes will provide a foundation for further research and practical applications in the field of civil engineering.

3. Materials Used

This section details the materials utilized in this research, including the concrete mix design, chemical agents for the experimental procedure, and the epoxy coating selected for enhancing the durability of concrete structures against chemical attacks.

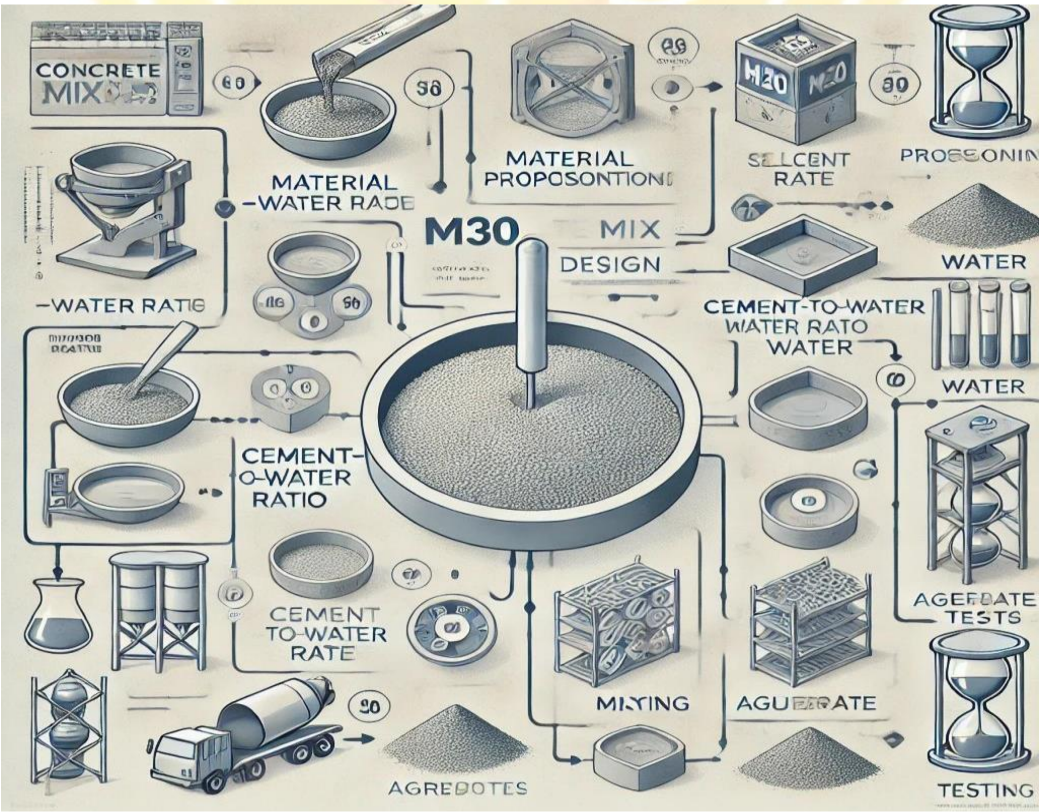

Figure 3: CMD Flowchart

3.1. Concrete Mix Design

The concrete used in this study is M30-grade concrete, which is a medium-strength concrete commonly employed in various construction applications. The mix design adhered to the following proportions:
Cement: Ordinary Portland Cement (OPC) conforming to IS 8112.

Aggregates: **Coarse Aggregate**: Crushed stone aggregates with a maximum size of 20 mm, sourced from a local quarry, conforming to IS 383. **Fine Aggregate**: Sand from a natural river that satisfies IS 383 standards and goes through a 4.75 mm screen.
Water: Clean, potable water, free from impurities, was used for mixing and curing, conforming to IS 456 standards.
Water-Cement Ratio: The water-cement ratio was maintained at 0.45 to achieve desired workability and strength.

3.2. Chemical Agents
To simulate the chemical attacks on concrete, the following chemical agents were prepared:
Sulphuric Acid (H_2SO_4): A 0.35% solution of sulphuric acid was prepared by diluting concentrated sulphuric acid with water. This solution was used to assess the impact of sulphuric acid on the mechanical properties of the concrete specimens.
Sodium Chloride (NaCl): A 0.35% solution of sodium chloride was prepared by dissolving the appropriate amount of salt in water. This solution was used to evaluate the effect of chloride on concrete durability.

3.3. Epoxy Coating
The epoxy coating selected for this research is a commercially available two-component epoxy resin known for its excellent adhesion, chemical resistance, and durability. The specific features of the epoxy coating include:
Composition: The epoxy coating consists of a resin and a hardener, which are mixed in a specified ratio before application.
Application Method: The epoxy was applied to the concrete surfaces using a brush and roller technique to ensure a uniform layer. The coating was allowed to cure for a specified period, ensuring optimal bonding and effectiveness against chemical ingress.
Performance Characteristics: The epoxy coating is designed to provide a robust barrier against chemical penetration, enhance the mechanical characteristics of the underlying concrete, and improve the overall durability of the structure.
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3.4. Testing Equipment
In addition to the materials, the following equipment was used during the testing phase:
Universal Testing Machine (UTM): For conducting compressive strength tests on concrete cubes.
Flexural Testing Machine: For evaluating the flexural strength of beam specimens.
Split-Tensile Testing Setup: For determining the split-tensile strength of cylindrical specimens.
Environmental Chamber: To maintain controlled curing conditions during the specimen preparation phase.

The materials utilized in this study are critical to evaluating the performance of M30 concrete under chemical attack conditions. The combination of well-defined concrete mix design, targeted chemical agents, and protective epoxy coatings sets the foundation for assessing the durability and effectiveness of mitigation strategies against chemical degradation in concrete structures.

4. Results and Discussion
This section presents the findings from the mechanical testing of M30 concrete specimens exposed to sulphuric acid and sodium chloride, as well as those treated with epoxy coatings. The results are discussed in relation to the impact of chemical attacks on the mechanical characteristics of concrete, highlighting the effectiveness of epoxy coatings as a protective measure.

4.1. Compressive Strength Results
The CST of concrete specimens was measured at 28, 14, and 7 days of curing.
Control Group: The control specimens exhibited a compressive strength of approximately 38.5 N/mm² at 28 days.
Sulfuric Acid Group: Specimens exposed to 0.35% sulfuric acid demonstrated a decrease in compressive strength, with values recorded at 32.3 N/mm², reflecting a 16% reduction compared to the control group. This reduction is attributed to the reaction between sulfuric acid and calcium hydroxide in the concrete, leading to the formation of gypsum and subsequent loss of structural integrity.
Chloride Group: The specimens exposed to 0.35% sodium chloride displayed a compressive strength of 32.7 N/mm², indicating a 15% decrease relative to the control group. The corrosion of steel reinforcement due to chloride ingress contributes to this reduction, compromising the load-bearing capacity of the concrete.
Epoxy Coated Group: After applying epoxy coatings to specimens previously exposed to sulfuric acid and chloride, the compressive strengths were measured at 35.3 N/mm² and 36.2 N/mm², respectively. This represents

a significant increase of 9% for sulfuric acid-exposed specimens and 12% for chloride-exposed specimens, demonstrating the efficacy of epoxy coatings in restoring mechanical strength.

4.2. Flexural Strength (FS) Results

FS tests were conducted to evaluate the resistance of concrete specimens to bending forces.

Control Group: The control specimens exhibited a FS of 5.2 N/mm² at 28 days.

Sulfuric Acid Group: Specimens subjected to sulfuric acid showed a FS of 4.0 N/mm², representing a 23% decrease from the control group. This reduction is primarily due to the deterioration of the concrete matrix caused by acid attack, which weakens the bond between aggregates.

Chloride Group: The specimens exposed to sodium chloride exhibited a flexural strength of 4.3 N/mm², a reduction of 18% compared to the control group. Similar to compressive strength, the corrosive effect of chlorides contributes to weakening the concrete structure.

Epoxy Coated Group: After epoxy treatment, the flexural strength for sulfuric acid-exposed specimens increased to 4.8 N/mm², indicating a recovery of 19.1%. For chloride-exposed specimens, the flexural strength improved to 4.6 N/mm², reflecting a 10% increase. The epoxy coating effectively reinforced the concrete surface, helping to bridge micro-cracks and enhancing overall structural integrity.

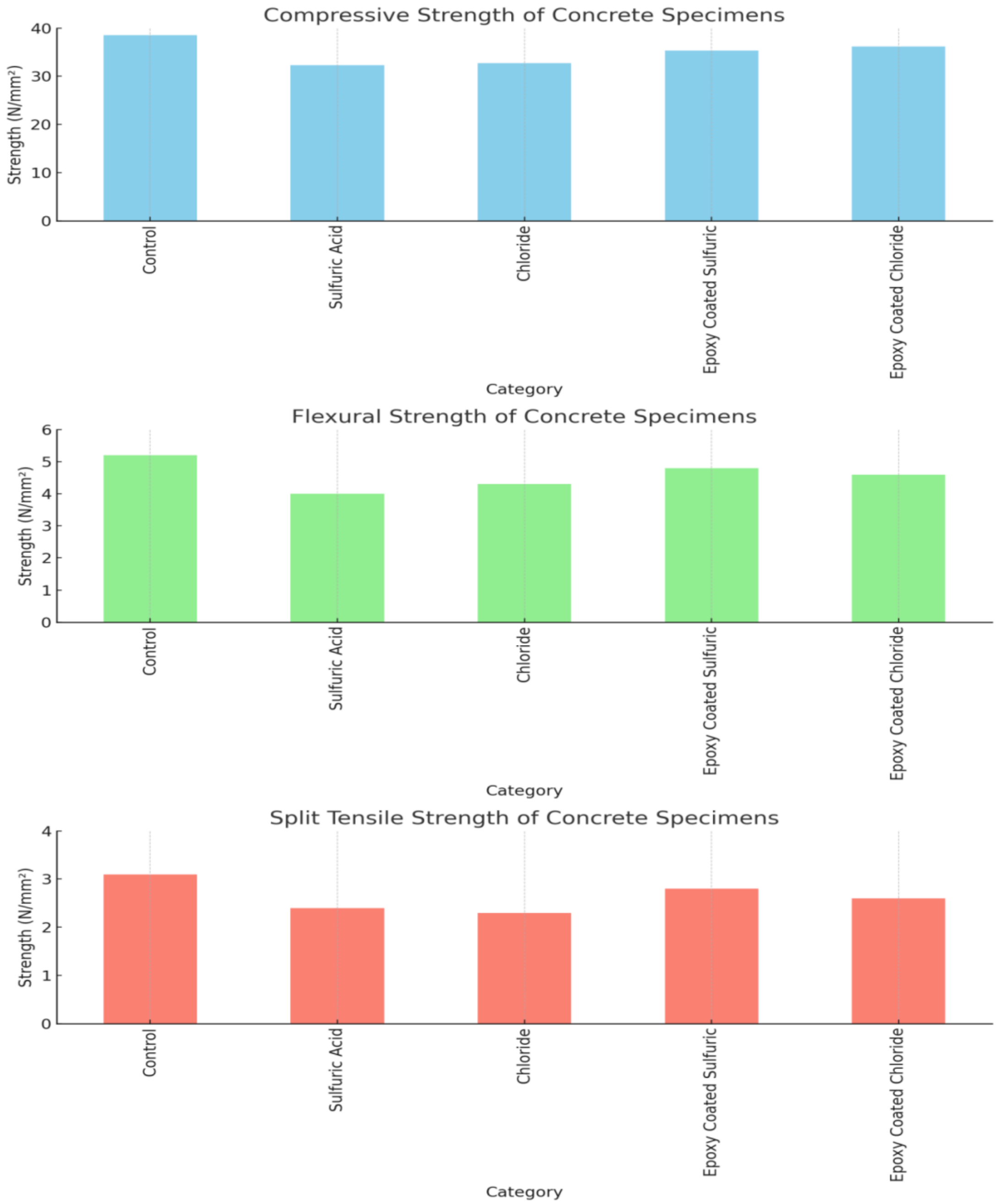

Figure 4: concrete strength results

4.3. Split-Tensile Strength Results

The STS of cylindrical specimens was evaluated to determine their resistance to axial tension.

Control Group: The control specimens demonstrated a split-tensile strength of 3.1 N/mm² at 28 days.

Sulphuric Acid Group: Specimens exposed to sulfuric acid showed a split-tensile strength of 2.4 N/mm², reflecting a decrease of 24%. The acidic environment disrupts the concrete matrix and reduces its tensile capacity.

Chloride Group: For specimens subjected to chloride, the split-tensile strength measured 2.3 N/mm², a 25% reduction compared to the control. The presence of chloride ions exacerbates the deterioration of concrete through corrosion mechanisms.

Epoxy Coated Group: After applying epoxy coatings, the split-tensile strength for sulphuric acid-exposed specimens increased to 2.8 N/mm², a recovery of 15%. For chloride-exposed specimens, the split-tensile strength improved to 2.6 N/mm², indicating a 12% increase. The epoxy coatings provided a protective layer that enhanced the tensile strength of the concrete.

Table 1: Concrete results table

Test Condition	Compressive Strength (N/mm^2)	Flexural Strength (N/mm^2)	Split Tensile Strength (N/mm^2)
Control	38.5	5.2	3.1
Sulfuric Acid	32.3	4.0	2.4
Chloride	32.7	4.3	2.3
Epoxy Coated Sulfuric	35.3	4.8	2.8
Epoxy Coated Chloride	36.2	4.6	2.6

4.4. Discussion of Results

It clearly indicates that exposure to chemical agents such as sulphuric acid and sodium chloride has a detrimental impact on the mechanical properties of M30 concrete. The observed reductions in flexural, compressive and STSs highlight the vulnerability of concrete structures in aggressive environments.

Effect of Chemical Attacks: The reduction in mechanical properties can be attributed to the reactions between the acidic or saline solutions and the components of the concrete. Sulphuric acid leads to the formation of gypsum, which weakens the concrete matrix, while chlorides cause corrosion of the embedded steel reinforcement, resulting in spalling and loss of load-bearing capacity.

Efficacy of Epoxy Coatings: The significant improvements in mechanical properties after applying epoxy coatings demonstrate their effectiveness in mitigating the effects of chemical degradation. By sealing the concrete surface and preventing further ingress of harmful chemicals, epoxy coatings enhance both the durability and strength of concrete structures. The ability of epoxy to restore mechanical properties after exposure to aggressive chemicals makes it a viable protective measure in construction practices.

Practical Implications: The findings of this study underscore the importance of implementing protective strategies, such as epoxy coatings, in the design and maintenance of concrete structures. Given the increasing prevalence of aggressive environmental conditions due to climate change and industrial activities, adopting such mitigation measures is essential for extending the service life of concrete infrastructures.
In summary, the results of this study provide compelling evidence of the adverse effects of chemical attacks on the mechanical properties of M30 concrete. Furthermore, the successful application of epoxy coatings illustrates a practical solution for enhancing the durability of concrete structures. Future research should continue to explore the long-term performance of epoxy-coated concrete in various environmental conditions to establish comprehensive guidelines for its application in construction.

5. Conclusion

This research focused on assessing the durability of M30 concrete structures subjected to chemical attacks from sulphuric acid and sodium chloride, along with evaluating the protective capabilities of epoxy coatings. The findings indicate that chemical exposure significantly deteriorates the mechanical properties of concrete, leading to reductions in flexural, compressive, and STSs. The following are the study's key findings:
Impact of Chemical Attacks: The exposure of concrete to 0.35% sulphuric acid resulted in a 16% reduction in CST, a 23% decrease in flexural strength, and a 24% decrease in split-tensile strength. Similarly, exposure to 0.35% sodium chloride led to a 15% reduction in compressive strength, an 18% decrease in flexural strength, and a 25% decrease in split-tensile strength. These results demonstrate the vulnerability of concrete structures in aggressive environments and highlight the necessity for protective measures.

Effectiveness of Epoxy Coatings: The application of epoxy coatings significantly improved the mechanical characteristics of concrete specimens previously exposed to chemical attacks. After treatment, specimens exposed to sulfuric acid showed a 9% increase in CSt, a 19.1% recovery in flexural strength, and a 15% improvement in split-tensile strength. For chloride-exposed specimens, increases of 12%, 10%, and 12% in flexural, compressive, and STSs, respectively, were observed. This underscores the efficacy of epoxy coatings in mitigating chemical degradation and enhancing the durability of concrete structures.

Practical Implications: The results of this study emphasize the importance of using protective strategies, such as epoxy coatings, to extend the service life of concrete infrastructures. With increasing exposure to aggressive environments due to climate change and industrial activities, implementing these protective measures is essential for maintaining structural integrity and reducing maintenance costs.

In conclusion, the findings highlight the critical need for ongoing research into the long-term performance of epoxy-coated concrete under various environmental conditions. Further studies should aim to establish comprehensive guidelines for the use of epoxy coatings in construction, ensuring that concrete structures remain resilient against chemical attacks throughout their service life.

Abbreviation

Split-tensile strength = STS
Compressive Strength Test = CST
Universal Testing Machine = UTM.
Concrete Mix Design = CMD

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