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Performance Evaluation of Crystalline Admixture Blended High-Performance Concrete for Sustainable and Long-Life Infrastructure

PRUTHVI ROUT[1], Mr. SHIVANSHU PATEL[2]
[1] *M.Tech. Scholar, School of Civil Engineering, Faculty of Engineering and Technology, Madhyanchal Professional University Bhopal, M.P*
[2] *Assistant Professor, School of Civil Engineering, Faculty of Engineering and Technology, Madhyanchal Professional University Bhopal, M.P.*

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Corresponding Author:
PRUTHVI ROUT

Abstract:

High-Performance Concrete (HPC) has become an essential construction material for modern infrastructure due to its superior strength, durability, and long-term performance. However, concrete structures exposed to aggressive environments are vulnerable to the ingress of chloride ions, which can initiate reinforcement corrosion and reduce service life. The present study investigates the influence of crystalline admixture on the mechanical and durability properties of M60 grade High-Performance Concrete. Two concrete mixes were prepared: a control mix without crystalline admixture and an experimental mix incorporating crystalline admixture. The performance of both mixes was evaluated through compressive strength tests at 7, 28, and 56 days, along with durability assessments using the Rapid Chloride Penetration Test (RCPT) and Rapid Chloride Migration Test (RCMT). The results showed that the concrete containing crystalline admixture exhibited higher compressive strength at all curing ages, achieving 59.37 MPa, 83.56 MPa, and 89.92 MPa at 7, 28, and 56 days, respectively, compared to the control mix. The RCPT value decreased from 650 Coulombs for the control mix to 562 Coulombs for the crystalline admixture concrete, while the chloride migration coefficient was reduced from 2.16×10^{-12} m²/s to 1.41×10^{-12} m²/s, indicating significantly improved resistance to chloride penetration. The enhanced performance is attributed to pore refinement, matrix densification, and the continued formation of crystalline reaction products, resulting in a denser and less permeable concrete microstructure. The findings demonstrate that crystalline admixture is an effective material for improving both the strength and durability of High-Performance Concrete, making it suitable for reinforced concrete structures exposed to aggressive environmental conditions.

Keywords: High-Performance Concrete (HPC), Crystalline Admixture, Compressive Strength, Durability, Rapid Chloride Penetration Test (RCPT), Rapid Chloride Migration Test (RCMT), Chloride Resistance, Permeability, M60 Concrete, Sustainable Infrastructure

1. Introduction

Concrete is the most widely used construction material in the world due to its versatility, availability, and cost-effectiveness. However, conventional concrete often suffers from durability-related issues such as cracking, permeability, and deterioration under aggressive environmental conditions. These limitations reduce the service life of structures and increase maintenance costs. To overcome these challenges, the development of High-Performance Concrete (HPC) has gained significant importance in modern civil engineering.

High-Performance Concrete is specifically designed to provide superior strength, durability, and long-term performance compared to normal concrete. It is characterized by low water-cement ratio, high workability, and enhanced mechanical and durability properties. The incorporation of supplementary cementitious materials and advanced chemical admixtures further improves its microstructure, making it denser and less permeable. Despite these advancements, micro-cracking due to shrinkage, thermal stresses, and loading remains a critical issue that can compromise durability over time.

In recent years, crystalline admixtures have emerged as an innovative solution to enhance the durability and self-healing capability of concrete. These admixtures are hydrophilic in nature and react with water and unhydrated cement particles to form insoluble crystalline structures within the pores and capillary networks of concrete. This crystalline formation blocks the pathways for water and harmful chemicals, significantly reducing permeability. Moreover, crystalline admixtures have the unique ability to promote self-healing of micro-cracks, typically up to a certain width, by reactivating in the presence of moisture and forming additional crystals.

The integration of crystalline admixtures into High-Performance Concrete leads to a new class of material that combines high strength with enhanced durability and sustainability. This modified HPC exhibits improved resistance to chloride ion penetration, sulphate attack, and water ingress, which are the primary causes of reinforcement corrosion and structural degradation. As a result, it becomes highly suitable for critical infrastructure such as bridges, marine structures, tunnels, water-retaining structures, and foundations exposed to harsh environments.

From a sustainability perspective, the use of crystalline admixture blended HPC contributes to the reduction of environmental impact by extending the service life of structures and minimizing the need for repairs and rehabilitation. Longer-lasting structures reduce material consumption, energy usage, and carbon emissions associated with reconstruction. Additionally, improved durability supports the concept of life-cycle cost efficiency, which is a key consideration in modern infrastructure development. This study focuses on the performance evaluation of crystalline admixture blended High-Performance Concrete, with particular emphasis on its mechanical properties such as compressive strength and split tensile strength, as well as durability parameters including permeability, chloride resistance, and sulphate resistance. Advanced testing methods such as Rapid Chloride Penetration Test (RCPT), Rapid Chloride Migration Test (RCMT), and water permeability tests are used to assess the durability performance. Microstructural analysis was carried out using Scanning Electron Microscopy (SEM) and Energy Dispersive X-ray Analysis (EDAX) to evaluate the microstructural characteristics of the concrete and to assess the influence of crystalline admixture on pore refinement and matrix densification. The primary objective of this research is to evaluate whether the incorporation of crystalline admixtures can significantly enhance the performance of HPC and make it a viable material for sustainable and long-life infrastructure. By improving resistance to environmental degradation and enabling self-healing properties, crystalline admixture blended HPC has the potential to redefine durability standards in the construction industry.

2. Literature Review

Riza Suwondo et al (2024) the construction industry is increasingly challenged by the combined pressures of climate change and rapid urbanization, which demand the development of advanced materials capable of enhancing the durability, strength, and sustainability of civil infrastructure. In this context, the present research investigates the effectiveness of crystalline waterproofing admixtures (CWA) in improving the performance of concrete. CWAs function by reacting with water and unhydrated cement particles to form insoluble crystalline structures that block capillary pores and micro-cracks, thereby reducing permeability and enhancing long-term durability. To evaluate their impact, a comprehensive experimental program was conducted on different concrete mixes incorporating varying percentages of CWA, with key tests including slump (to assess workability), compressive strength (to measure load-bearing capacity), water penetration (to evaluate permeability), and chemical resistance tests using aggressive solutions such as sulfuric acid (H_2SO_4) and hydrochloric acid (HCl). The results demonstrate that the inclusion of CWA significantly improves concrete performance: the addition of 1% CWA increases compressive strength from 41 MPa to 43.2 MPa (a 5.4% improvement), while 2% CWA further enhances it to 43.5 MPa (a 6.1% increase), indicating a denser and more refined microstructure. More notably, water penetration depth is drastically reduced, from 43 mm in control concrete to 20 mm (53% reduction) with 1% CWA and to 15 mm (65% reduction) with 2% CWA, confirming a substantial improvement in impermeability. Furthermore, CWA-treated concrete exhibits enhanced resistance to chemical attack, as evidenced by higher retained compressive strength and lower mass loss after exposure to acidic environments, which is critical for structures in industrial or marine conditions. An important finding is that concrete with CWA and ordinary cement (Type I) achieves performance comparable to that of sulfate-resistant cement (Type V), suggesting that CWA can serve as an effective and economical alternative for improving durability. Overall, this study contributes valuable insights into modern concrete technology by demonstrating that the incorporation of crystalline admixtures not only enhances mechanical properties and durability but also supports sustainable construction practices by extending the service life and reducing maintenance requirements of concrete structures in diverse and aggressive environments.

Ravi Kumar Shetiya et al (2024) Self-healing concrete incorporating crystalline admixtures and surface coatings represents an advanced approach to improving the durability and service life of concrete structures by enabling the material to autonomously repair micro cracks and pores that typically act as pathways for water and aggressive agents. In this study, four different concrete mixes were developed to evaluate how these crystalline components influence key mechanical and durability properties compared to conventional concrete. The investigation included assessments of crack-bridging capability, compressive strength, flexural strength, and water absorption, providing a comprehensive understanding of both structural performance and long-term durability. A combination of destructive (such as compressive and flexural strength tests), semi-destructive, and non-destructive testing methods was employed to ensure accurate evaluation of the material behavior. The self-healing efficiency was specifically examined by inducing damage in specimens and then analyzing crack closure through visual inspection and microstructural techniques, which revealed the formation of crystalline products that block and seal cracks. Additionally, fresh concrete properties were studied using slump cone and air content tests, indicating that while workability may slightly vary, the mixes remain practical for construction use. The results clearly show that the inclusion of crystalline admixtures and coatings enhances the internal microstructure.

3. Methodology

In this study, Ordinary Portland Cement (OPC), 53 grade was used as the primary binding material. The cement conforms to IS 269:2015, which is the Indian Standard specification for Ordinary Portland Cement and ensures that the cement meets the required quality, strength, and performance criteria. The term 53-grade indicates that the cement develops a minimum compressive strength of 53 MPa after 28 days under standard testing conditions. This grade is commonly used in structural concrete applications where higher early strength and improved performance are required.

Additionally, the cement was selected so that its tricalcium aluminate (C_3A) content remained between 5% and 8%. C_3A is one of the major chemical compounds present in cement and significantly influences the initial setting time, hydration rate, heat generation during hydration, and resistance to sulphate attack.

Maintaining the C_3A content within the 5–8% range helps control the hydration process and provides more consistent behavior during experimentation. Lower and controlled C_3A content generally reduces excessive heat evolution and improves durability, especially when evaluating permeability, chloride resistance, sulphate resistance, and long-term performance characteristics of High-Performance Concrete (HPC) containing crystalline admixtures. This selection ensured uniform cement properties throughout the study and minimized variations that could affect the interpretation of the mechanical, durability, and microstructural test results.

Crystalline Admixture

A crystalline admixture conforming to the requirements of IS 9103, ASTM C494, and DIN 18998 was used in this study. Crystalline admixture is a dry, cementitious powder added to concrete during batching to provide integral, long-term waterproofing through a chemical reaction within the concrete matrix. It is composed of reactive chemical compounds, typically silica-based and other proprietary active ingredients, which are activated in the presence of moisture and unhydrated cement particles. This reaction produces insoluble crystalline structures that develop within the capillary pores and micro-cracks of concrete.

These crystals progressively grow and block the pathways for water and aggressive chemicals, thereby significantly reducing the permeability of concrete. A key advantage of this system is its self-healing capability, as the crystalline reaction can reactivate upon subsequent exposure to moisture, enabling the sealing of hairline cracks of up to approximately 0.4 mm in width. Furthermore, crystalline admixtures are classified as a Permeability Reducing Admixture for Hydrostatic conditions (PRAH), crystalline admixtures enhance the durability and water resistance of concrete under hydrostatic pressure. They also provide improved protection against reinforcement corrosion, chemical attack, and freeze–thaw damage, making them particularly suitable for structures such as basements, tunnels, water-retaining structures, and marine constructions where long-term waterproofing performance is essential.

Figure 1 Experimental setup for compressive strength testing.

Table 1 Material proportions for 1 m³ of M60 High-Performance Concrete (HPC) incorporating crystalline admixture under saturated surface dry (SSD) condition

Cement content (kg)	430
Fly Ash (kg)	170
Micro silica (kg)	30
20 MM (kg)	574
10MM (kg)	381
C Sand (kg)	677

Water (kg)	145
Chemical Admixture (kg)	8.82
% of Chemical Admixture (by weight of cementitious material)	1.40
Corrosion Inhibitor (kg)	0.50
Crystalline Admixture (kg)	5.04
% of Crystalline (by weight of cementitious material)	0.80
Density of concrete (kg/m³)	2421

4. Results and Discussion

This paper presents and discusses the results obtained from the experimental investigation carried out on M60 grade High-Performance Concrete (HPC) incorporating crystalline admixture. The study was undertaken to evaluate the influence of crystalline admixture on the fresh, mechanical, durability, and microstructural characteristics of concrete. The performance of the crystalline admixture blended HPC was assessed by comparing it with the corresponding control mix prepared under identical conditions.

A comprehensive experimental programme was conducted to evaluate the fresh, mechanical, durability, and microstructural performance of High-Performance Concrete incorporating crystalline admixture. The investigation included slump and slump flow tests, compressive strength and split tensile strength tests, Rapid Chloride Penetration Test (RCPT), Rapid Chloride Migration Test (RCMT), chloride and sulphate content tests, water permeability and water absorption tests, as well as SEM and EDAX analyses. However, this paper presents and discusses only the compressive strength, RCPT, and RCMT results, which provide a representative assessment of the mechanical strength and chloride durability performance of the investigated concrete.

Compressive strength

The compressive strength results of the High-Performance Concrete (HPC) mixes with and without crystalline admixture are presented in Table 2 and Figure 2. The results indicate that the incorporation of crystalline admixture resulted in higher compressive strength at all curing ages compared to the control mix.

Table 2 Compressive strength of High-Performance Concrete

Compressive strength N/mm^2	7 Days	28 Days	56 Days	Remarks
With Crystalline	59.37	83.56	89.92	Mean compressive strength determined from nine cube specimens at 7 and 28 days, and three cube specimens at 56 days.
Without Crystalline	56.14	79.76	86.21	

The results further show that both mixes exhibited a progressive increase in compressive strength with curing age; however, the concrete containing crystalline admixture consistently maintained higher strength values throughout the testing period. The trend observed in Figure 2 demonstrates that the incorporation of crystalline admixture contributed positively to compressive strength development. The improved performance may be attributed to the formation of insoluble crystalline products within the concrete matrix, which help refine the pore structure and enhance matrix densification. Overall, the concrete incorporating crystalline admixture exhibited superior compressive strength performance compared to the control mix at all curing ages considered in the present investigation.

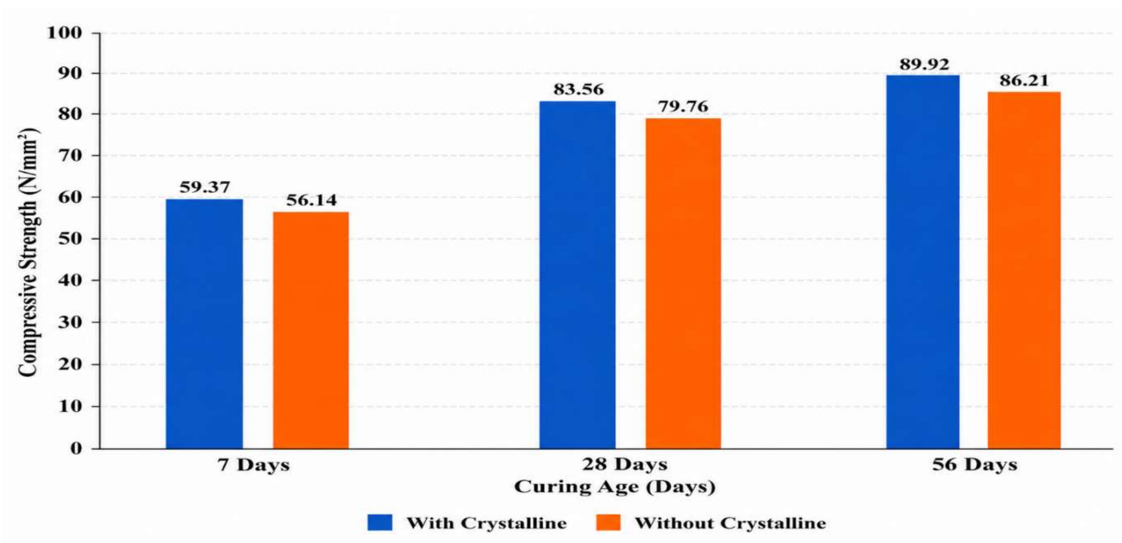

Figure 2 Compressive Strength of High-Performance Concrete

Durability Characteristics

The durability performance of High-Performance Concrete (HPC) incorporating crystalline admixture was evaluated through Rapid Chloride Penetration Test (RCPT), Rapid Chloride Migration Test (RCMT), chloride content analysis, sulphate content analysis, water permeability test, and water absorption test. The results obtained are presented in Table 3 and compared with those of the control mix without crystalline admixture.

Table 3 Durability test of High-Performance Concrete

Durability Parameter Results				
Sr. No.	**Tests**	**With Crystalline**	**Without Crystalline/Control Mix**	**Remarks**
1	RCPT	562 Coulomb	650 Coulomb	Mean value determined from three specimens tested at 56 days.
2	RCMT	1.41×10^{-12} m²/s	2.16×10^{-12} m²/s	Mean value determined from three specimens tested at 56 days.

The RCPT results indicate that the concrete incorporating crystalline admixture recorded a charge passed value of 562 Coulombs, compared to 650 Coulombs for the control mix. The lower charge passed value indicates reduced chloride ion permeability and improved resistance to chloride ingress. This improvement may be attributed to the refinement of the pore structure and reduction in pore connectivity within the concrete matrix.

Similarly, the RCMT results showed a chloride migration coefficient of 1.41×10^{-12} m²/s for the concrete containing crystalline admixture, whereas the control mix recorded 2.16×10^{-12} m²/s. The lower migration coefficient confirms the reduced mobility of chloride ions through the concrete matrix, indicating enhanced resistance against chloride penetration under aggressive exposure conditions.

5. Conclusion

The present experimental investigation evaluated the effect of crystalline admixture on the performance of M60 grade High-Performance Concrete (HPC) by comparing it with a conventional control mix. Based on the experimental results, the following conclusions can be drawn:

The incorporation of crystalline admixture significantly enhanced the compressive strength of High-Performance Concrete at all curing ages. The concrete with crystalline admixture achieved compressive strengths of **59.37 MPa, 83.56 MPa, and 89.92 MPa** at 7, 28, and 56 days, respectively, compared to **56.14 MPa, 79.76 MPa, and 86.21 MPa** for the control mix. This improvement is attributed to the formation of insoluble crystalline products that densify the cementitious matrix and reduce internal pore spaces.

The durability performance of the crystalline admixture concrete was superior to that of the control mix. The Rapid Chloride Penetration Test (RCPT) recorded a lower charge passed value of **562 Coulombs**, compared to **650 Coulombs** for the control mix, indicating reduced chloride ion permeability and improved resistance to aggressive environments.

The Rapid Chloride Migration Test (RCMT) also confirmed the enhanced durability of the crystalline admixture concrete. The chloride migration coefficient decreased from **2.16×10^{-12} m²/s** for the control mix to **1.41×10^{-12} m²/s** with crystalline admixture, demonstrating a significant reduction in chloride ion transport through the concrete matrix.

The improvement in both strength and durability can be attributed to the self-healing and pore-blocking action of crystalline admixtures. These admixtures react with moisture and unhydrated cement particles to form insoluble crystalline products that block capillary pores and microcracks, resulting in a denser and less permeable concrete microstructure.

Based on the experimental findings, it can be concluded that crystalline admixture not only improves the mechanical performance of High-Performance Concrete but also substantially enhances its long-term durability, making it a promising material for sustainable and long-lasting concrete construction.

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