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ENHANCING CONCRETE DURABILITY THROUGH CRYSTALLINE WATERPROOFING ADMIXTURES: A COMPREHENSIVE PERFORMANCE EVALUATION

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ABSTRACT: The construction industry grapples with significant challenges posed by climate change and urbanization, driving the imperative for innovative materials to elevate the performance and durability of civil infrastructure in the pursuit of sustainability. In this research, the application of crystalline waterproofing admixtures (CWA) to improve concrete durability is investigated. The study aims to analyze the effect of CWA on concrete performance by conducting a series of tests on different concrete mixtures. These tests include slump tests, compressive strength tests, water penetration tests, and chemical resistance tests using sulfuric acid (H_2SO_4) and hydrochloric acid (HCl) solutions. The results indicate that incorporating CWA into concrete leads to notable improvements. Specifically, the addition of 1% CWA enhances compressive strength from 41 MPa to 43.2 MPa, a 5.4% improvement. Similarly, 2% CWA results in a 6.1% increase, reaching 43.5 MPa. Water penetration tests indicate substantial benefits, with 1% CWA reducing penetration from 43 mm to 20 mm (53% improvement), and 2% CWA further reducing it to 15 mm (65% improvement). Additionally, CWA-treated concrete exhibits improved chemical resistance, resulting in higher compressive strength values and lower mass loss percentages after chemical exposure. The combination of CWA with cement type I demonstrates comparable performance to cement type V in terms of compressive strength and chemical resistance. The research contributes to the understanding of concrete technology, guiding engineers in selecting suitable materials to enhance the longevity and serviceability of concrete structures in various environmental conditions.

Keywords: Additive material, Admixtures, Concrete durability, Chemical resistance, Permeability, Workability

1. INTRODUCTION

The global construction industry, amid significant shifts driven by climate change, urbanization, and sustainability imperatives, is increasingly demanding advanced materials for modern civil infrastructure. In this evolving landscape, a critical emphasis on long-term durability emerges as pivotal, addressing the challenges posed by climate change and rapid urbanization. The feasibility and widespread acceptance of emerging technologies now hinge significantly on their capacity to uphold robust performance over extended periods [1–3]. Recognizing the pivotal role of long-term durability, the industry's commitment to resilient structures becomes paramount. Insufficient durability not only compromises structural integrity but also elevates the risks of damage and loss of functionality and escalates maintenance costs [2]. This paradigm shift underscores the critical need for construction practices that fortify structures against the ongoing impacts of climate change and urbanization, ensuring that modern infrastructure stands resilient in the face of evolving environmental demands.

Concrete durability is intricately linked to the degradation of its microstructure and the infiltration of deleterious substances. Microstructural degradation refers to the deterioration of the internal arrangement of concrete components, a phenomenon influenced by factors like chemical reactions and environmental exposure. Chlorides, sulfates, and marine salt are common agents causing deterioration, often leading to the loss of both the physical and mechanical properties of concrete [4,5]. Various chemical and mineral admixtures, as well as alkali-activated geopolymers, have been explored to control and enhance concrete durability[6–9].

In marine environments, combined sulfate and chloride attack is a primary factor responsible for the chemical degradation of concrete structures. While sulfate ions can cause volume expansion through secondary ettringite and gypsum formation, their impact is altered when combined with chloride attack. In such cases, the volume expansion of secondary ettringite and gypsum is suppressed due to factors such as reduced availability of certain compounds, as they react swiftly with chloride ions to form chloroaluminate compounds and soluble calcium chloride. Additionally, the solubility of gypsum and ettringite may increase due to the reduction of pH in the presence of chloride ions [10,11]. Nonetheless, deterioration can still occur as a result of pore formation resulting from the leaching of calcium ions from the internal structural arrangement of the cement phases. Calcium-based salts, including gypsum, ettringite, and calcium chloride, dissolve in the low pH solution that develops due to the ingress of chloride ions, further exacerbating the degradation process.

Several mitigation techniques have been adopted to combat concrete degradation in environments where sulfate and chloride attacks coexist. These strategies encompass the utilization of various additives like silica fume (SF), fly ash (FA), ground granulated blast furnace slag (GGBFS), limestone cement, and self-consolidating Portland limestone cement-based concretes [12–16]. By incorporating these additives, concrete structures demonstrate improved resistance and resilience, safeguarding their long-term durability in challenging marine environments.

There has been a development of special admixtures aimed at reducing water penetration in concrete, which plays a crucial role in enhancing concrete durability. These admixtures, as per ACI 212.3 R-10 [17], fall into two categories: Permeability-reducing admixtures for non-hydrostatic conditions, previously known as "moisture repellent admixtures," suitable for resisting water under limited pressure but not suitable for concrete exposed to water under significant pressure; and permeability-reducing admixtures for hydrostatic conditions, also known as "waterproofing materials," capable of effectively resisting water under pressure and employed in watertight structures such as tanks, foundations, and containments.

Among these admixtures, crystalline waterproofing admixtures (CWA) consist of Portland cement, specially treated quartz sand, and a combination of "active chemicals." The specific chemical composition of these active chemicals is proprietary and undisclosed by manufacturers [18–20]. These chemicals react with water and cement particles in the concrete, resulting in an increased density of calcium silicate hydrates and the formation of pore-blocking precipitates in capillaries and microcracks [21]. Consequently, concrete with incorporated CWA exhibits reduced water penetration depth compared to reference concrete, as supported by previous research[21,22]. Moreover, CWA is known to facilitate self-healing of cracks[23–27]. Different CWAs have been found to produce distinct crystals responsible for water penetration reduction and concrete self-healing. Self-healing capacity varies across studies, with some experiments reporting complete healing of cracks up to 0.1 mm wide, while others demonstrate healing even for cracks with widths of up to 0.4 mm. Studies suggest that CWAs are more effective in mixes with higher water-binder ratios as increased water content promotes self-healing. Besides water penetration and self-healing, CWA has also been reported to improve concrete resistance to freeze-thaw cycles, reduce chloride ion penetration, enhance resistance to sulfate attack and have a negligible impact on concrete compressive strength.

In Indonesia, the utilization of cement Type V is prevalent in concrete applications that demand exceptional sulfate resistance, as recommended by ACI 318-19 [28]. Cement Type V is utilized for its exceptional sulfate resistance due to its reduced tricalcium aluminate (C_3A) content. By minimizing C_3A, the potential for sulfate attack is significantly diminished, making it ideal for structures exposed to sulfate-rich environments, such as coastal structures, piers, underwater tunnels, and wastewater treatment facilities [29,30]. While Type V cement may exhibit slightly lower early-age compressive strength, its ability to prevent damage from expansive sulfate compounds ensures long-term concrete durability and structural integrity in aggressive environments with high sulfate levels.

This research presented herein focuses on investigating the application of CWA as a means to enhance concrete durability. This study aims to systematically investigate the impact of CWA on concrete performance, addressing specific knowledge gaps regarding its influence on compressive strength, water penetration resistance, and chemical resistance. This study involves a systematic investigation using varied doses of CWA in concrete mixes, focusing on compressive strength, water penetration resistance, and chemical resistance. By comparing results with benchmark cement types (type I and type V), the research aims to deepen insights into CWA's impact on concrete properties in challenging environments. Anticipated outcomes include valuable benchmark data and enhanced scientific understanding, providing practical guidance for CWA application in concrete engineering for long-term performance and sustainability in challenging environments.

2. RESEARCH SIGNIFICANCE

This research holds paramount significance as it addresses pressing challenges in the construction industry, offering novel insights into the application of crystalline waterproofing admixtures (CWA) in concrete. By systematically evaluating the impact of CWA on workability, compressive strength, and durability, the study contributes valuable knowledge for engineers and builders. The findings guide the selection of materials for diverse construction scenarios, enhancing the longevity, structural integrity, and overall performance of concrete structures. As climate change, urbanization, and sustainability concerns intensify, the research provides crucial advancements in developing resilient and sustainable civil infrastructure.

3. METHODOLOGY

3.1 Material

For this research, concrete with a compressive strength of 35 MPa, classified as C35, has been chosen due to its common use in infrastructure in. C35 concrete exhibits a balance between strength and workability, making it well-suited for applications where durability and performance in adverse conditions are crucial. The design mix is carried out following the guidelines specified in the Indonesian Standard SNI 2834-2000 [31] as shown in Table 1.

The methodology employs a water-cement ratio of 0.45, a crucial factor influencing concrete properties. This ratio is carefully chosen to balance optimal workability during construction with achieving desired strength and durability characteristics in the cured concrete.

The concrete specimens utilized in this study are labelled as I-0, I-1, I-2, and V-0, where the initial letter denotes the type of cement employed, and the numerical value signifies the composition of admixtures. The study incorporates Type I and Type V Portland cement, adhering to the ASTM C150 [32] standards. The methodology includes Type I cement as a benchmark for general use, evaluating CWA performance, while Type V cement addresses sulfate resistance in relevant environments.

Table 1 Concrete mix design

Mixtures	I-0	I-1	I-2	V-0
Cement	410	410	410	410
Coarse aggregate	1020	1020	1020	1020
Fine aggregate	784	784	784	784
Water	203	203	203	203
CWA	-	4.1	8.2	-

All units in kg/m³

To ensure uniformity in the concrete mix, the CWA is incorporated during the batching process. Subsequently, the concrete specimens are cast in moulds and demoulded, after which they undergo a 28-day curing period in water, following the guidelines outlined in SNI 2493-2011 [33]. The industry-prescribed curing method, crucial for assessing CWA in enhancing concrete durability, involves a standardized timeframe to ensure a comprehensive evaluation of properties. Immersion curing in water aligns with industry standards, promoting optimal hydration and facilitating a thorough examination of CWA's long-term effects on concrete durability.

3.2 Experimental Procedures

In pursuit of the research objective, a comprehensive series of experimental procedures has been meticulously devised as presented in Table 2. The evaluation of hardened concrete revolves around widely accepted and standardized testing methods. The compressive strength assessment quantifies load-bearing capacity, crucial for structural integrity evaluation, while the water penetration test elucidates moisture resistance, vital for assessing durability. These tests, strategically designed within the experimental framework, provide targeted information, contributing to a holistic understanding of concrete durability and the effectiveness of crystalline waterproofing admixtures under various stressors.

The compressive strength assessment is conducted on cylindrical specimens with dimensions of ϕ150x300 mm³, following the ASTM C39 guidelines[34]. The dimensions for cylindrical specimens align with standard practices in concrete testing, providing a widely recognized and accepted basis for evaluating compressive strength.

Table 2: Test methods

Test	Number of samples	Standard
Compressive strength	3 per mix	ASTM C39[34]
Water penetration	3 per mix	EN 12390-8 [35]
Chemical resistance	3 per mix	ASTM C1898 [36]

Concrete durability is evaluated through water penetration and chemical resistance tests. For the water penetration test, prismatic specimens measuring 200 × 200 × 120 mm³ are employed, adhering to the EN 12390-8 specifications [35]. The specimens undergo testing under a pressure of 5.09 kg/cm² for 72 hours.

The chemical resistance test is executed following the procedures outlined in ASTM C1898 [36]. Similar to the compressive strength test, ϕ150x300 mm³ cylinder specimens are utilized. The initial curing of these specimens is conducted underwater for 28 days, after which they are immersed in a 5% H_2SO_4 and 5% HCl solution for up to 70 days. This duration aligns with real-world applications, simulating long-term durability requirements in acidic environments. Regular solution replacement every 14 days ensures consistent, rigorous testing. This approach in the chemical resistance test provides robust evaluation, enhancing the study findings' relevance to practical construction scenarios.

The study adopts standardized methods to assess concrete performance, specifically focusing on compressive strength, water penetration resistance, and chemical durability. Established testing protocols facilitate confident comparisons, offering insights into the effectiveness of the crystalline admixture. Rigorous durability tests contribute to understanding the admixture's potential in critical construction projects.

4. RESULTS AND DISCUSSIONS

4.1 Slump

Fig. 1 presents the slump test outcomes, showcasing variations in slump values among concrete mixtures. Cement type I concrete had a 100 mm slump, which increased to 115 mm with 1% CWA, and further to 120 mm with 2% CWA, indicating improved workability. Type V cement concrete exhibited the highest slump at 130 mm, suggesting superior workability compared to type I mixes.

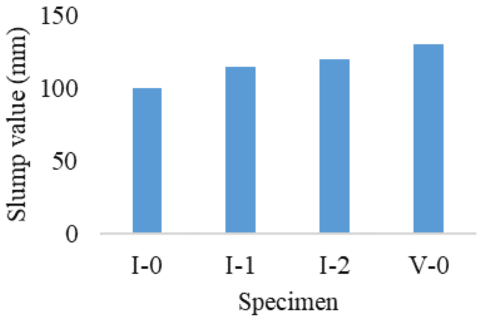

Fig.1 Slump test results

Variations in slump values indicate the positive influence of CWA on concrete workability, reducing segregation and simplifying construction processes. The higher slump value in Type V cement underlines the positive impact of cement type on flowability, enhancing overall project quality and efficiency, particularly in scenarios where optimal workability is critical.

4.2 Compressive Strength

Fig. 2 shows the compressive strength results. It is noteworthy that all tested specimens surpassed the target compressive strength requirement for C35 concrete grade, which signifies their adequate performance in meeting the specified engineering standards.

Improvements in compressive strength with added CWA in cement type I demonstrate the admixture's beneficial impact on concrete's mechanical properties. This enhanced strength is crucial for overall durability and load-bearing capacity. Slight variations in compressive strength values underscore the sensitivity of concrete properties to changes in cement type and CWA dosage.

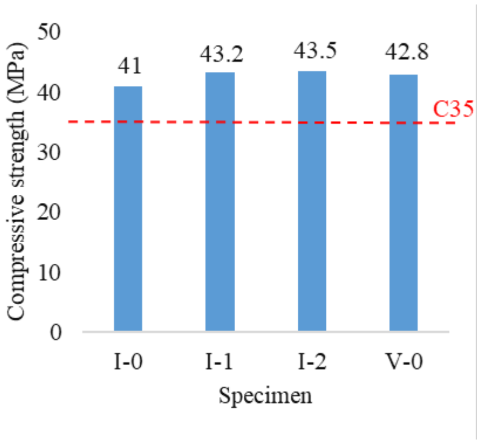

Fig.2 Compressive strength test results

The compressive strength values obtained for concrete with cement type V (42.8 MPa) are near those of cement type I mixes containing different CWA dosages (43.2 MPa for 1% CWA and 43.5 MPa for 2% CWA). Slight variations in compressive strength among concrete mixtures may result from interactions between CWA and the cement matrix, affecting calcium silicate hydrates and pore-blocking precipitates. However, the overall result highlights that cement type V, known for superior sulfate resistance, maintains compressive strength compared to cement type I mixes with CWA. This finding is crucial for applications in extreme sulfate exposure e.g. foundations in sulfate bearing soils.

4.3 Water Penetration

The results of the water penetration test provide crucial insights into the effectiveness of CWA in enhancing the water resistance of the concrete mixtures. The recorded water penetration depths for each concrete mixture are presented in Fig. 3.

The significant decrease in water penetration depth with CWA effectively obstructs water ingress, crucial for applications in moisture-rich environments. This improvement enhances resistance to moisture-related damage, freeze-thaw cycles, and reinforcing element corrosion. The reduced water penetration depth contributes substantially to prolonged service life, structural integrity, and overall durability of concrete structures, making CWA valuable for challenging environmental conditions.

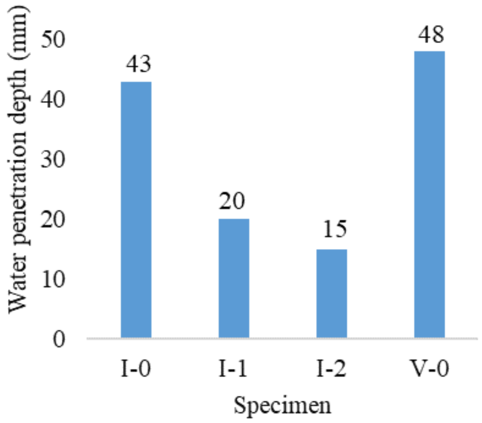

Fig.3 Water penetration test results

CWA enhances water resistance in cement type I concrete, outperforming type V. At a 2% dosage, type I with CWA achieving the lowest penetration depth (15 mm), offering significant protection against water ingress compared to other mixtures.

Water penetration and compressive strength results affirm the suitability of CWA-treated cement type I. It outperforms type V by achieving lower water penetration depths and comparable compressive strength, making it advantageous for applications requiring both water resistance and strength.

The water penetration test results highlight the effectiveness of CWA in enhancing the water resistance of concrete. These outcomes, particularly the penetration depth values, carry practical significance for diverse construction scenarios. In environments like coastal or marine settings, minimizing water penetration is crucial for long-term durability. Lower penetration depths, as indicated in this study, signify improved moisture resistance, reducing the risk of deterioration, reinforcing structural integrity, and extending concrete lifespan. These findings offer practical insights for engineers, aiding material selection in various construction applications.

4.4 Chemical Resistance

The chemical resistance test, which involved immersing the concrete samples in H_2SO_4 and HCl solutions for 70 days, provides valuable insights into the performance of the different concrete mixtures under aggressive chemical exposure. These acids were chosen for their real-world relevance in industrial and environmental scenarios, reflecting aggressive agents that can impact concrete durability. Sulfuric acid is common in wastewater treatment, while hydrochloric acid is prevalent in various industrial processes. Testing concrete resistance to these acids provides vital information for structures in chemical-exposed environments, offering insights into durability and suitability for practical applications where protection against aggressive agents is essential.

The compressive strength results, both before and after immersion in the chemical solutions are presented in Fig. 4. The results reveal a reduction in compressive strength for all concrete mixtures following exposure to both H_2SO_4 and HCl solutions. The observed decrease in compressive strength after exposure to chemical solutions indicates the vulnerability of concrete structures to aggressive chemical environments. The acids initiate reactions within the cementitious matrix, leading to the breakdown of the concrete's microstructure and compromising its load-bearing capacity.

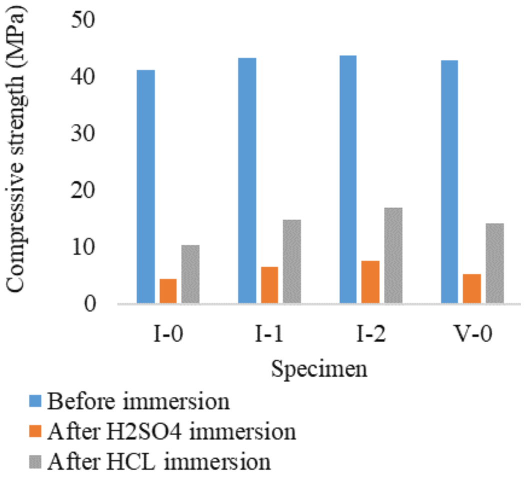

Fig. 4 Concrete compressive strength test results before and after immersion in H_2SO_4 and HCl

The addition of CWA to cement type I concrete notably enhances chemical resistance. Compressive strength values in H_2SO_4 and HCl solutions for 1% and 2% CWA dosages surpass plain cement type I and are comparable to or slightly better than type V cement concrete. CWA proves effective in mitigating chemical exposure, enhancing concrete durability. The observed rise in compressive strength post-immersion suggests CWA helps maintain microstructure integrity and minimizes chemical attack.

The chemical resistance test highlights CWA's role in enhancing the chemical durability of cement type I concrete. The increased compressive strength in H_2SO_4 and HCl solutions for CWA-treated mixtures suggests its potential to improve performance in chemically aggressive environments. These findings contribute to concrete technology knowledge, guiding material selection for construction projects facing chemical exposure challenges.

The loss in mass of concrete after immersion in H_2SO_4 and HCl solutions provides critical information regarding the extent of chemical attack and degradation experienced by the different concrete mixtures. The percentage of mass loss for each concrete mixture is presented in Fig. 5.

The results illustrate that all concrete mixtures exhibited mass loss after immersion in both H_2SO_4 and HCl solutions. The magnitude of mass loss serves as a crucial indicator of the severity of chemical attack on the concrete. Addressing the practical implications, the extent of mass loss correlates directly with the expected lifespan and performance of concrete structures in aggressive chemical environments. Higher mass loss percentages signify more pronounced chemical deterioration, potentially compromising the structural integrity and longevity of the concrete.

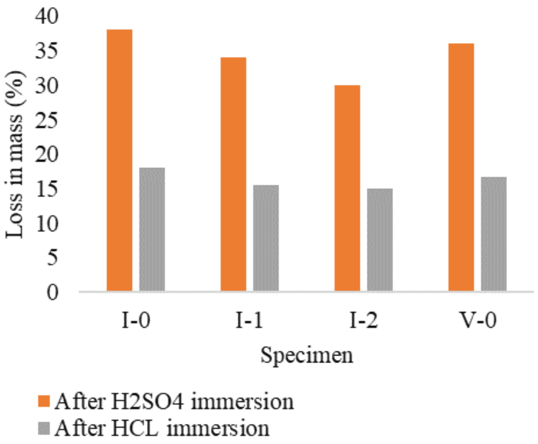

Fig. 5 Loss in mass of concrete

The inclusion of CWA in cement type I concrete significantly reduced mass loss after immersion in H_2SO_4 and HCl solutions. Concrete with 1% and 2% CWA exhibited lower mass loss than plain cement type I, indicating enhanced resistance to chemical degradation. Additionally, type V cement, with improved sulfate resistance, showed slightly lower mass loss than cement type I with CWA after immersion, suggesting inherent protection by type V cement, further enhanced by the admixture.

The correlation between mass loss and compressive strength provides key insights into chemical resistance. Concrete with lower mass loss retains higher compressive strength after exposure to acids, emphasizing the intrinsic link between chemical resistance and mechanical properties. This correlation guides concrete design, highlighting the need to balance chemical durability and structural robustness for optimal performance in aggressive environments.

Consistent with previous studies[25,27], the current research demonstrates that the incorporation of CWA contributes to improvements in workability, compressive strength, and water penetration resistance. These findings align with the general understanding that CWA, by promoting the formation of crystalline structures within the concrete matrix, enhances its overall durability and performance. The observed increase in compressive strength is in line with numerous studies indicating that CWA-treated concrete often exhibits higher strength values compared to untreated concrete.

This study, integrating slump, compressive strength, and chemical resistance tests, highlights the suitability of concrete mixes for specific applications. CWA enhances workability, facilitating efficient construction processes and minimizing segregation risk. The correlation between reduced water penetration depth and improved chemical resistance underscores CWA's efficacy in obstructing water ingress, enhancing concrete durability in challenging environments.

Moreover, the correlation between mass loss and compressive strength underscores the link between chemical resistance and mechanical properties in concrete. Concrete with lower mass loss maintains higher compressive strength after exposure to aggressive chemicals, emphasizing the need to balance durability and structural robustness in design. These results affirm the suitability of CWA-enhanced concrete for applications requiring enhanced workability and durability, such as coastal or industrial settings. The integrated findings guide engineers in tailoring concrete formulations for longevity and reliability in diverse scenarios.

5. CONCLUSIONS

Based on the comprehensive findings obtained from the slump tests, compressive strength tests, water penetration tests, and chemical resistance tests, several key conclusions can be drawn:

1. Crystalline Waterproofing Admixture (CWA) Effectiveness: Incorporating 1% and 2% Crystalline Waterproofing Admixture (CWA) in cement type I concrete markedly enhanced workability and fluidity, as revealed by the slump test. Additionally, the compressive strength test underscored CWA's positive impact on mechanical properties, yielding higher values.
2. Water Penetration Resistance: The water penetration test results showed that CWA significantly reduced the depth of water

penetration into the concrete. Concrete with CWA at 1% and 2% dosages exhibited lower water penetration depths compared to plain cement type I and even rivalled the performance of concrete with type V cement.

3. Chemical Resistance: Concrete mixtures with 1% and 2% CWA doses displayed enhanced chemical resistance, with higher compressive strength and lower mass loss after exposure to H_2SO_4 and HCl solutions, outperforming plain cement type I concrete.
4. Cement Type V and CWA Synergy: The comparison with type V cement emphasizes the synergy between cement type V and CWA in enhancing concrete performance. Cement type V, renowned for superior sulfate resistance, exhibited comparable compressive strength to cement type I with CWA admixture. This suggests that cement type V, combined with CWA, can offer enhanced protection against chemical attack, reinforcing the concrete's resistance to chemicals.
5. Engineering Applications: CWA exhibits versatile applications in engineering, suitable for coastal structures, industrial facilities, high-rise construction, and more. Its ability to enhance concrete durability, water resistance, and chemical resistance makes it a valuable solution for diverse engineering scenarios, ensuring longevity and sustainability against various environmental challenges.

This study unequivocally establishes the efficacy of Crystalline Waterproofing Admixture (CWA) in enhancing multiple facets of cement type I concrete. With 1% and 2% CWA doses, improvements in workability, compressive strength, and resistance to water penetration and chemical degradation were consistently demonstrated. The synergy between CWA and cement type V further accentuates the concrete's resilience to chemical attack. While these findings hold practical implications for construction projects, acknowledging the study's limitations, such as controlled laboratory conditions, underscores the need for further research in diverse field settings to validate and extend these insights. This study not only answers the specific research question but also opens avenues for future investigations into optimizing CWA-enhanced concrete for real-world applications.

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