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# Study on Autogenous Self-Healing Concrete Using Crystalline Admixtures

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## Abstract

The shrinkage, thermal changes and external loadings of concrete structures can cause cracking, leading to increased water and aggressive agent penetration and deterioration and shortened service life. A sustainable solution to mitigate crack propagation has been found to be autogenous self-healing utilizing the inherent healing properties of cementitious materials. Most of the self-healing methods have received extensive research interest, especially crystalline admixtures which encourage the growth of non-soluble crystalline products to seal cracks and enhance the impermeability of concrete. This study focuses on the effectiveness of the crystalline admixture to improve self-healing capacity of concrete. The concrete specimens were formed having various doses of crystalline admixtures and the specimens were subjected to a controlled crack creation in a laboratory environment. After a curing period, the healing criteria for the appearance of cracks, recovery of compressive strength, reduction of water permeability, sorptivity and ultrasonic pulse velocity testing were applied. The experimental results show that the use of crystalline admixtures show significant enhancement in crack closure as well as improvement of mechanical and durability properties of concrete, compared to conventional concrete. Concrete containing crystalline admixtures exhibited higher healing efficiency, higher strength recovery, less water penetration, less sorptivity and improved internal concrete integrity. The results suggested that use of crystalline admixtures could be considered a viable and eco-friendly option to prolong the service life of concrete structures and decrease maintenance efforts and life cycle costs. Thus, the proposed solution has a great potential for the development of long-term and sustainable smart infrastructure applications.

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## 1. Introduction

Concrete is one of the most commonly used construction materials due to its strength, durability and cost-effectiveness. In its service life, however, the formation of cracks is inevitable that is caused by shrinkage, thermal stresses, mechanical loading and environmental effects. These cracks allow water, chlorides and other corrosive materials to infiltrate into the structure and result in corrosion of the reinforcement, lower durability and higher maintenance costs. Traditional methods like the application of a surface coating or epoxy injection can be time-consuming, expensive and are not as effective to repair small or hard-to-reach cracks. So it has become an important research area of sustainable infrastructure to develop concrete that can autonomously repair cracks.

Unreacted cement particles and mineral products precipitation is the natural hydration and sealing of small cracks that does not require any intervention (autogenous self-healing). The inherent healing property of ordinary concrete, however, is rather limited and is a function of crack width and curing conditions. For enhancement of this ability, a new type of admixture, called crystalline admixtures, has been developed which introduces insoluble crystals into cracks and pores by reacting with water and hydration products of the cements. They seal cracks, decrease permeability, and help increase the durability of concrete, without the need for extra repair work.

Previous studies have shown the potential of using crystalline admixtures, although most investigations have concentrated on single performance

characteristics (such as crack closure or durability), and potential for mechanical recovery and healing performance has been investigated using only a few performance evaluation methods. Thus a detailed experimental study is needed to be conducted to gain insight to the effect of dosage of crystalline admixture on the healing effect and durability of concrete. In this study, the autogenous self-healing performance of the concrete containing various dosages of crystalline admixtures is studied in an experimental manner. The suggested method values crack-healing efficiency using image-based crack measurements and compressive strength recovery, water permeability reduction, sorptivity and ultrasonic pulse velocity. The results offer a thorough understanding of the benefits of crystalline admixture for improving the durability and service life of concrete, and the development of smart infrastructure to promote sustainable and low maintenance structures.

## 2. Literature Review

Concrete has an intrinsic capacity for self-healing of small cracks that is caused by the continued hydration of unreacted cement particles and the precipitation of calcium carbonate in cracks [1]. This mechanism works effectively depending on the crack width, moisture, curing conditions and cement composition [10]. Narrow cracks can heal naturally under certain conditions, however the ability of the concrete to heal is very limited and conventional concrete structures are only durable in the short term [2, 7].

This drawback can be overcome by using crystalline admixtures as an internal self-healing agent. These admixtures cause interaction with water and cement hydration products that result in an insoluble crystalline structure that fills cracks and pores, thus decreasing the permeability and durability [3] of the concrete. The crystalline products will grow if water is available, thus allowing for reapplication of crack sealant as many times as the concrete requires during its life.The crystalline products will grow in the presence of water, making repeated crack sealing possible throughout the life of the concrete [9]. X-ray diffraction analysis has also shown that the use of crystalline admixtures significantly enhance the autonomous healing performance and durability in cementitious composites in recent studies [6], [8], [11].

Concrete made with crystalline admixtures has been consistently found to possess better crack closure, water absorption, impermeability and mechanical recovery than conventional concrete [3, 5]. Extensive review research has also shown that crystalline admixtures have a beneficial effect on crack-healing efficiency and they can help increase the life span of concrete constructions with decrease maintenance requirements [2], [6], [7], [12]. Despite these improvements, the majority of the current research has concentrated on a single performance parameter (crack closure, permeability or compressive strength) and only a few investigations have explored several mechanical and durability values in a common experimental set-up [2]. Moreover, the effect of these various dosages of the crystalline admixtures has not been systematically examined through the use of other performance measures, such as [8, 11, 12]. Hence, a systematic experimental study is needed to quantify the image-based crack-healing efficiency, recovery of compressive strength, decrease in water permeability, decrease in sorptivity and ultrasonic pulse velocity of the concrete produced by using the crystalline admixtures in order to get a complete evaluation of the admixtures for sustainable self-healing concrete applications.

## 3. Materials And Methods

### 3.1 Materials

In this study, the main binder used was ordinary Portland cement (OPC) based on the relevant standards. The fine aggregate was natural river sand with suitable grading and crushed granite with a nominal maximum size of 20mm was used as coarse aggregate. Concrete mixing and curing were carried out with clean potable water to ensure a proper mixture for cement hydration. The powdered commercial crystalline admixture was added to the concrete mixtures to add autogenous self-healing properties. The admixture is made up of reactive chemicals which react with water and unhydrated cement particles to generate an insoluble crystalline product within the pore structure and cracks that decreases permeability and increases the durability of the concrete. All materials were stored under controlled lab conditions prior to mixing, to ensure consistent quality over the experimental program. The physical characteristics of the materials investigated are shown in Table 1.

**Table 1.** Material Properties

| Material | Property | Value |
|---|---|---|
| Ordinary Portland Cement | Specific Gravity | 3.15 |
| Fine Aggregate | Specific Gravity | 2.64 |
| Fine Aggregate | Fineness Modulus | 2.70 |
| Coarse Aggregate | Maximum Size | 20 mm |
| Coarse Aggregate | Specific Gravity | 2.72 |
| Water | pH | 7.0 |
| Crystalline Admixture | Physical Form | Powder |
| Crystalline Admixture | Specific Gravity | 1.15 |

### 3.2 Mix Design

Four concrete mixtures were blended to assess the effect of the use of the crystalline admixture in the autogenousself healing performance of concrete. A mixture with no admixture of crystals was taken as the reference or control mix and three other mixes contained various percentages of the crystal

admixture, by weight of cement. All the mixes had the same water to cement ratio of 0.45 to provide a fair comparison. The amounts of fine aggregate, coarse aggregate and water were fixed and the dosage of the crystalline admixture was varied. The advantage of this was to allow the effect of the admixture applied to crack healing, mechanical recovery and the durability properties to be studied independently. Crystalline admixtures details and water–cement ratio used for each mix are presented in Table 2.

**Table 2.** Crystalline Admixture Dosages and Water–Cement Ratio

| Mix ID | Crystalline Admixture (% by CementWeight) | Water-Cement Ratio |
|---|---|---|
| CM | 0 | 0.45 |
| CA-1 | 1 | 0.45 |
| CA-2 | 2 | 0.45 |
| CA-3 | 3 | 0.45 |

### 3.3 Specimen Preparation

Concrete mixtures were mixed in the laboratory using a drum mixer and mixing was carried out in the same manner as specified in the standard mixing procedure. The initial dry mixing was done of cement, fine aggregate, coarse aggregate and crystalline admixture; this was done to get uniformity in the mixing. Then, water was poured in little by little and mixing was done till a uniform concrete mix is achieved. The fresh concrete was placed in steel moulds for the type of mechanical and durability test required and was compacted on a vibration table to expel entrapped air. The specimens cast were then placed under plastic bins to minimize moisture loss, and demoulded after 24 hours. All the specimens were then cured for 28 days at room temperature in clean water for crack generation and self-healing evaluation. Each concrete mixture and test condition was tested three times for each item, and the values given are the average of the experimental results. For the specimen size, loading rate, test standards, permeability specimen size, and ultrasonic pulse velocity path length, the values should be given to correspond to the actual experimental procedure followed in the study. The overall experimental procedure is shown in Figure 1.

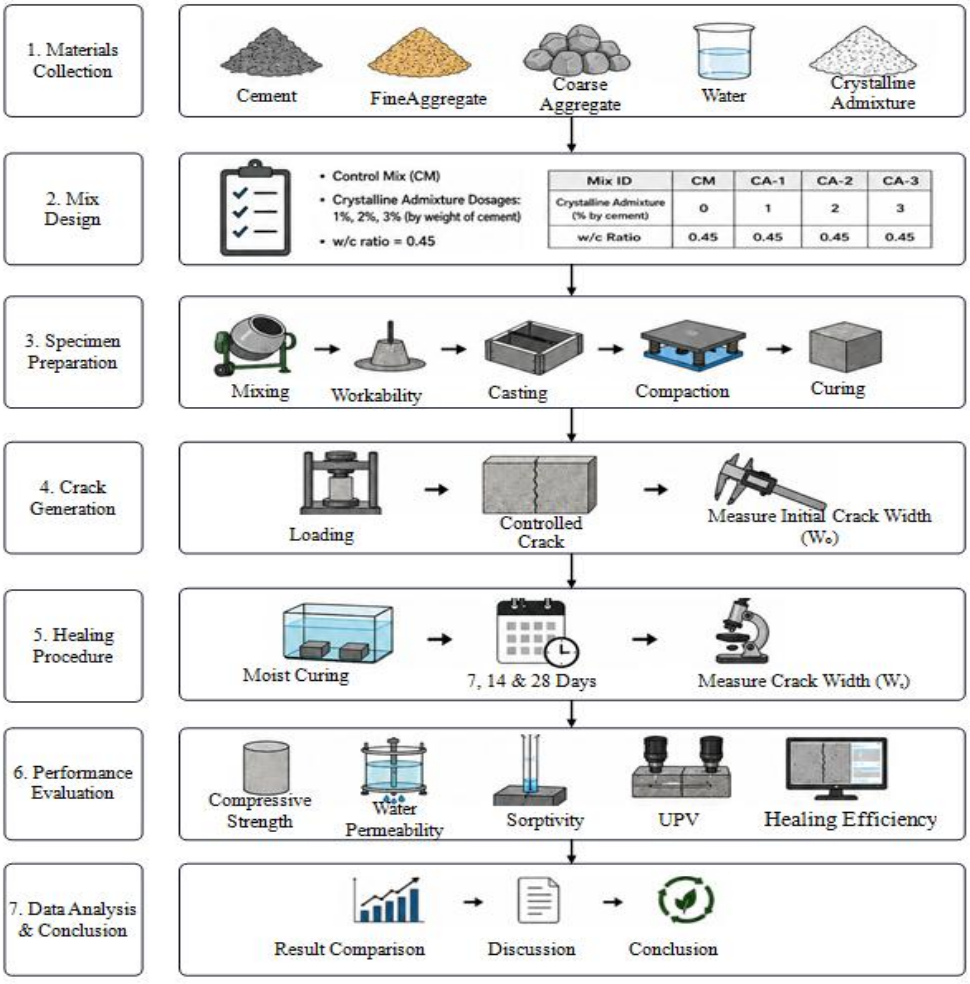


**Fig. 1.** Experimental Workflow

### 3.4 Crack Generation and Healing Procedure

The cured concrete specimens were made with controlled surface cracks in a compression testing machine. The loads were incrementally applied until the desired crack width was attained, but before failure of the structure occurred. Initial cracks widths were determined by a digital microscope and software. The specimens were subjected to moist curing after the crack generation to encourage the autogenous healing through the process of continued cement hydration and the development of crystals. Images of the cracks were taken periodically throughout the healing time period, and residual crack width was measured using the same image analysis technique. The performance of cracking healing was quantified for each concrete mixture by the reduction in width of the cracks.

### 3.5 Performance Evaluation

Five complimentary performance indicators were used to evaluate the self-healing performance of the concrete. The reduction of crack width was measured, and crack-healing efficiency was determined based on the following.

$$HE_W(\%) = \frac{W_0 - W_t}{w_0} \times 100 _____ (1)$$

where $W_0$ is the initial crack width and$W_t$ is the crack width after healing.

The recovery of compressive strength was calculated using

$$SR(\%) = \frac{f_{ch}}{f_{uc}} \times 100 _____ (2)$$

where$f_{ch}$ is the compressive strength of the healed specimen and $f_{uc}$ is the compressive strength of the corresponding uncracked specimen.

The improvement in water resistance was evaluated using the water permeability reduction expressed as

$$PR(\%) = \frac{P_0 - P_t}{P_0} \times 100 _____ (3)$$

Where$P_0$ and $P_t$ denote the permeability values before and after healing, respectively.

The capillary water absorption characteristic was determined through the sorptivity equation

$$S = \frac{1}{\sqrt{t}} _____ (4)$$

where$I$ is the cumulative water absorption and ttt is the elapsed time.

The internal quality and integrity of concrete were assessed using ultrasonic pulse velocity calculated as

$$UPV = \frac{L}{T} _____ (5)$$

where$L$ represents the pulse travel distance and $T$ is the measured travel time.

An image based crack measurement algorithm was used to quantify the crack closure with respect to the crack closing period, which was obtained from the initial crack width and the healed crack width. A set of experimental parameters were used in the investigation and they are given in Table 3. Three specimens per mixture and test condition were used for all tests. The values reported are the average of three measurements. Results are reported as mean ± standard deviation and the variability of the results were evaluated. One way analysis of variance was employed to determine if there were statistically significant differences between the concrete mixtures at the 0.05 level of significance if needed.

**Algorithm 1. Image-Based Crack Measurement and Healing Efficiency Assessment**

1. Prepare concrete specimens according to the selected mix design.
2. Cure the specimens for 28 days.
3. Generate controlled surface cracks.
4. Capture the initial crack images.
5. Measure the initial crack width.
6. Subject the specimens to moist curing.
7. Capture crack images after each healing interval.
8. Measure the healed crack width.
9. Calculate crack-healing efficiency.
10. Evaluate compressive strength recovery, water permeability reduction, sorptivity, and ultrasonic pulse velocity.
11. Compare the performance of all concrete mixtures.

**Table 3.** Experimental Parameters

| Parameter | Value |
|---|---|
| Water-cement ratio | 0.45 |
| Crystalline admixture dosage | 0–3% |
| Initial curing period | 28 days |
| Initial crack width | 0.20–0.40 mm |
| Healing environment | Moist curing |
| Healing evaluation | 7, 14, and 28 days |
| Performance metrics | 5 |

## 4. Results And Discussion

### 4.1 Crack-Healing Performance

Crack healing ability of the concrete mixtures was tested after 7, 14 and 28 days of moist curing. The average reduction of cracks during healing period is presented on Table 4. The trend of crack width for all mixtures was similar and decreased with the increase in curing time. The specimens with the crystalline admixture however, exhibited higher crack closure than the control mixture.

In the case of the control mixture (CM), the reduction of crack width from 0.30 mm to 0.115 mm was observed after 28 days. This decrease was primarily related to the ongoing hydration of cement and precipitation of calcium carbonate. In comparison, CA-1, CA-2, and CA-3 recorded final crack widths of 0.051, 0.025, and 0.023 mm, respectively. The reduced residual crack width found in the modified mixtures suggests that the crystalline admixture aided the formation of extra insoluble products in the cracks.

**Table 4.** Average Crack-Width Variation During the Healing Period

| Mix ID | Initial Crack Width (mm) | 7 Days (mm) | 14 Days (mm) | 28 Days (mm) |
|---|---|---|---|---|
| CM | 0.300 | 0.215 | 0.161 | 0.115 |
| CA-1 | 0.300 | 0.160 | 0.095 | 0.051 |
| CA-2 | 0.300 | 0.133 | 0.069 | 0.025 |
| CA-3 | 0.300 | 0.129 | 0.065 | 0.023 |

The crack-healing efficiencies corresponding to this are indicated in Table 5. Healing efficiency of control mixture was 61.7% after 28 days while that of CA-1, CA-2 and CA-3 were 82.9%, 91.8% and 92.5%, respectively, after 28 days. The healing efficiency of the mixtures at various curing ages is compared as shown in figure 2. No significant differences were seen between the 2% and 3% admixture dosages indicating that an increase in dosage beyond 2% was not significantly beneficial.

**Table 5.** Crack-Healing Efficiency of Concrete Mixtures

| Mix ID | 7 Days (%) | 14 Days (%) | 28 Days (%) |
|---|---|---|---|
| CM | 28.4 | 46.2 | 61.7 |
| CA-1 | 46.8 | 68.5 | 82.9 |
| CA-2 | 55.6 | 76.9 | 91.8 |
| CA-3 | 57.1 | 78.2 | 92.5 |

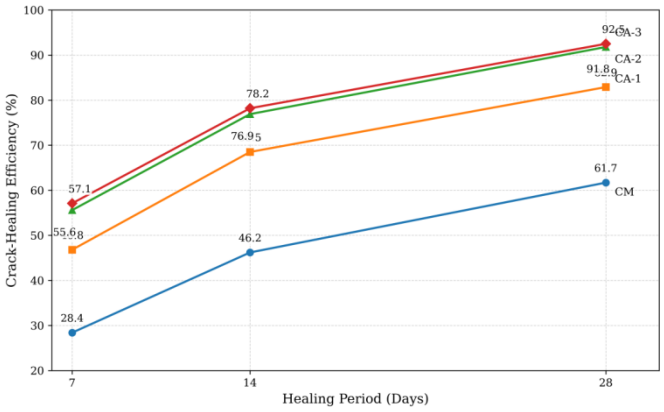


**Fig. 2.** Crack-Healing Efficiency of Concrete Mixtures at Different Healing Periods

The results show that moisture availability and crystalline admixture dosage significantly affected in terms of crack closure.Water continued to fill cracks over time and acted as a catalyst to the crystal formation.Due to the minimal difference between CA-2 and CA-3, it was determined that the 2% crystalline admixture dosage was the preferred dosage under the adopted performance–material balance as it resulted in nearly the same crack-healing performance that was measured, while using less admixture.

## 4.2 Compressive-Strength Recovery

The compressive-strength recovery analysis was conducted to see whether the crack-healing mechanism produced the recovery of mechanical properties of the concrete sample. Table 6 shows the compressive strength of uncracked, cracked before repair, repaired and recovered strength percentage for uncracked specimens.

**Table 6.** Compressive-Strength Recovery After 28 Days of Healing

| Mix ID | Uncracked Strength (MPa) | Cracked Strength (MPa) | Healed Strength (MPa) | Strength Recovery (%) |
|---|---|---|---|---|
| CM | 38.2 | 27.4 | 29.9 | 78.3 |
| CA-1 | 39.1 | 28.1 | 34.6 | 88.6 |
| CA-2 | 40.3 | 29.0 | 38.3 | 95.1 |
| CA-3 | 40.0 | 28.8 | 38.3 | 95.7 |

The strength of the control mixture recovered 78.3%. The use of crystalline admixture improved the recovery for CA-1 from 78.5% to 88.6%, for CA-2 from 89.0% to 95.1%, and for CA-3 from 93.0% to 95.7%. Figure 3 indicates that the four mixes have different strength recovery rates..

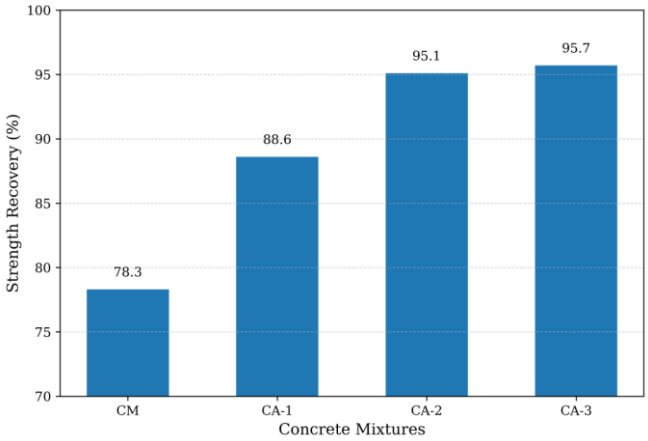


**Fig. 3.** Compressive-Strength Recovery of Concrete Mixtures After Healing

This increase in strength recovery is due to crack-filling and internal void fillers via hydration and crystalline products. These products helped to create a cementitious continuity and to allow stress to pass through the healed crack zone. No other CA has seen as much of an improvement as CA-3, with a 0.6 percentage point gain, but still 0.4 percentage points

primary care strength behind CA-2. Thus, CA-2 was selected as the best mixture for the adopted performance-Materials balance instead of being an absolute optimum mixture.

### 4.3 Durability Performance

To determine the recovery of resistance against water penetration, water permeability and sorptivity have been investigated. Table 7 shows the water permeability evaluation results before and after healing as well as the reduction in percentage, after 28 days of healing.

**Table 7.** Water-Permeability Performance of Concrete Mixtures

| Mix ID | Before Healing ((\times10^{-10}) m/s) | After Healing ((\times10^{-10}) m/s) | Permeability Reduction (%) |
|---|---|---|---|
| CM | 6.20 | 4.18 | 32.6 |
| CA-1 | 6.05 | 2.19 | 63.8 |
| CA-2 | 5.95 | 0.94 | 84.2 |
| CA-3 | 5.92 | 0.85 | 85.7 |

The control mixture showed 32.6% reduction in permeability while CA-1, CA-2 and CA-3 showed 63.8%, 84.2% and 85.7% reduction respectively. The significant decrease in the volume of crystalline-admixture mixtures shows that crack pathways and capillary pores were successfully closed by healing.

The sorptivity results are shown in Table 8. The initial sorptivity values were in the similar range of the mixtures, and increased increased of crystalline admixture dosage resulted in decreased value for the healed values.

**Table 8.**Sorptivity Performance of Concrete Mixtures After Healing

| Mix ID | Initial Sorptivity (mm/(\sqrt{\text{min}})) | Healed Sorptivity (mm/(\sqrt{\text{min}})) | Sorptivity Reduction (%) |
|---|---|---|---|
| CM | 0.0260 | 0.0220 | 15.4 |
| CA-1 | 0.0256 | 0.0175 | 31.6 |
| CA-2 | 0.0254 | 0.0146 | 42.5 |
| CA-3 | 0.0253 | 0.0142 | 43.8 |

**Table 9.** Ultrasonic Pulse Velocity Recovery of Concrete Mixtures After Healing

| Mix ID | UPV Recovery (%) |
|---|---|
| CM | 84.6 |
| CA-1 | 91.8 |
| CA-2 | 97.2 |
| CA-3 | 97.5 |

The sorptivity reduction was 15.4% for the control mixture, and 42.5% (CA-2) and 43.8% (CA-3). The water permeability and water sorptivity reductions are compared as a percentage in Figure 4. The two parameters were not the same physical units so percentage reduction was used for a direct comparison.

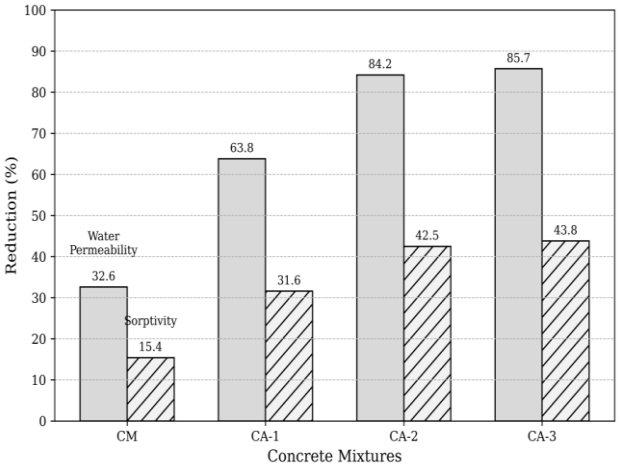


**Fig. 4.** Water-Permeability and Sorptivity Reduction of Concrete Mixtures

Durability test results demonstrate that there was a significant decrease in water transport in conjunction with the crack closure. This is important as it does not always mean the crack has closed completely and it would not mean recovery to be at the level of full durability. An improvement in permeability and sorptivity simultaneously indicates that the crystalline products filled both the surface cracks and the interconnected pores inside.

### 4.4 Ultrasonic Pulse Velocity Analysis

Ultrasonic pulse velocity was used as a non-destructive indicator of internal concrete quality. As shown in Table 8, the control mixture achieved a UPV recovery of 84.6%, whereas CA-1, CA-2, and CA-3 achieved 91.8%, 97.2%, and 97.5%, respectively.The increased UPV recovery indicates reduced internal discontinuities and improved compactness after healing. The results also agree with the compressive-strength and permeability findings. Specimens with greater crack closure generally demonstrated higher pulse-velocity recovery and lower water penetration. The small difference between CA-2 and CA-3 again indicates that the benefit of increasing the crystalline admixture dosage above 2% was limited.

### 4.5 Overall Discussion

Results of the combined tests indicate that crystalline admixtures were found to be effective in improving autogenous self-healing properties of concrete in a moist curing environment. The enhancements were

seen in the crack healing efficiency, compressive-strength recovery, reduction in water permeability, reduction in sorptivity, and ultrasonic pulse velocity recovery. The natural healing continues in the control mixture due to continued hydration and mineral precipitation, but the performance of the control mixture was not as good as the concrete mixtures with the crystalline admixtures.

The enhanced crack closure is believed to be the result of the production of the insoluble crystalline products in the cracks and in the pore network which over time cause a decrease in crack size and reduce the flow of water through the concrete matrix. The decrease of the water permeability and sorptivity, suggests that the crystalline products are effective in closing interconnected capillary pores, which increases the durability of the concrete. The higher compressive-strength recovery and ultrasonic pulse velocity also indicate that the healing products helped to improve the internal continuity and integrity of the cracked concrete. The concrete treated with 2% of the crystalline Mixer produced 91.8% Crack-healing efficiency, 95.1% Compressive-strength Recovery, 84.2% Water-permeability Reduction, 42.5% Sorptivity Reduction and 97.2% Ultrasonic pulse velocity Recovery among the investigated mixtures. The 3% crystalline admixture resulted in slightly higher results for some of the performance indicators but the increase was a small amount. Hence, it was concluded that the dosage of 2% crystalline admixture was the optimum dosage as it gives almost the same healing and durability performance at lesser quantity of admixture.

Overall, the results show that the use of crystalline admixtures is an effective solution for the enhancement of the self-healing ability and long-term durability of concrete based on crack propagation, water ingress and mechanical recovery. The properties of these crystalline admixtures make them an interesting material option for achieving long-lasting durability of concrete structures and minimizing maintenance needs for sustainable infrastructure projects.

## 5. Conclusion

In this study, the autogenous self-healing performance of the concrete using crystalline admixtures was examined through laboratory tests of the crack-healing efficiency, compressive-strength recovery, water-permeability reduction, sorptivity and ultrasonic pulse velocity. The results shows that the self-healing property of concrete, with the addition of crystalline admixture, is significantly better in comparison to the self-healing property of the mix without any admixture. Mechanical recovery and durability also increased with the formation of crystalline products, thus improving crack closure, which in turn helped to lower the amount of water passing through the concrete matrix. These enhancements help to boost the buildings structural strength, longevity and integrity. Of the investigated mixtures, the concrete with 2% crystalline admixture proved to be the optimum, from the overall performance point of view, with the adopted concept of the performance–material balance. It had a crack-healing efficiency of 91.8%, compressive-strength recovery of 95.1%, water-permeability reduction of 84.2%, sorptivity reduction of 42.5%, and ultrasonic pulse velocity recovery of 97.2%. The 3% dosage was shown to give slightly better values for some of the parameters, but with only small improvements, a 2% dosage will give a more efficient performance improvement/material utilisation balance. The results have proven that the concrete with crystalline admixtures is an efficient way to prepare durable and sustainable self-healing concrete, which can be used for building bridges, tunnels, water-retaining structures, foundations and other infrastructure in environments prone to water. The use of the proposed approach can result in a reduction of cracking and water leakage through the crack, thus decreasing maintenance requirements and service life for concrete structures. The present study, however, was performed under laboratory-controlled conditions and 28-day healing time. Further research is required on long-term development and performance of the self-healing concrete in different environments and with increasing crack width, cyclic loading and application of a combination of crystalline admixtures and supplementary cementitious materials (SCMs) to improve durability and sustainability in self-healing concrete.

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