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Self-healing Characteristic of Concrete Containing Capillary Crystalline Waterproofing Material

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Abstract

The self-healing properties of concrete are a key characteristic produced by capillary crystalline waterproofing material to mitigate microcracks. This study investigates the effects of varying (CCW) proportions (0, 0.5, 1.0 and 1.5 %) on M25 grade concrete, which was subjected to compressive strength tests to create controlled cracking. This study focused on analysed the crack filling mehanism in concrete containing capillary crystalline waterproofing material with barriers loading magnitude and determine the optimum inclusion of capillary crystalline waterproofing material in concrete with various cracks formation. The concrete mix included coarse and fine aggregates, ordinary Portland cement, and capillary crystalline waterproofing material. The materials used included coarse and fine aggregates, ordinary Portland cement, and capillary crystalline waterproofing material. The experiment utilized 100mm x 100mm x 100mm cube moulds with curing periods of 28 and 56 days, and included 36 samples with varying percentages of capillary crystalline waterproofing material. In this project, the methodology used for testing was compressive strength, Scanning Eletron Microscopy (SEM) and visual crack analysis. In these studies, the analyse the crack-filling mechanism in concrete enhanced with capillary crystalline waterproofing material shows in mix proportion 1.0% CCW inclusion and makes that inclusion was the optimum number for self-healing. Furthermore, the study explored the self-healing capabilities of concrete with capillary crystalline waterproofing material and aiming to enhance the permeability within 56 days post-loading. The results emphasize the theoretical and practical benefits of capillary crystalline waterproofing material as an additive for producing durable and sustainable concrete structures.

1. Introduction

The construction industry has experienced rapid growth worldwide, with numerous new developments emerging in both rural and urban areas. Building materials, including concrete, are essential for completing construction projects. However, cracks often appear in the cement concrete layers after a project is completed [1]. According to [2], these cracks can occur due to several factors, particularly when structures are subjected to overloading.

Additionally, cracks can also form due to thermal changes, whether from high or low temperatures. This phenomenon was demonstrated in an experiment conducted by [3], which aimed to induce cracks using high temperatures. Cracks can manifest in various forms, including surface cracks, deep cracks, and hairline cracks. These cracks can result from several causes, such as thermal changes, overloading, shrinkage during curing, and the settlement of the foundation. In a study by [4], a range of samples was tested to assess the relationship between force in Newtons (N) and displacement millimetres (mm).

However, there are numerous advanced technologies that aid in detecting cracks in concrete. As demonstrated by [5], the enhanced Crack Image Enhance and Detection (CIEAD-2) system can analyse images of concrete surface cracks, providing a clearer view of the cracks before treatment procedures are initiated.

Meanwhile, (CCW) materials have been introduced in the era of globalization to address these issues. These materials enhance the pore structure, reduce porosity, and provide protection by filling concrete capillaries and cracks. This is achieved through the diffusion of active compounds from (CCW) materials with water [6]. Crystalline waterproofing serves as a self-sealing mechanism for pores, microcracks, or hidden structural damage. It blocks these vulnerabilities with the formation of millions of needle-like crystals on the surface after reacting with water and cement [7].

The self-sealing properties of crystalline waterproofing are effective for micro-cracks smaller than 30 micrometres and macro-cracks up to 0.4 millimetres. Additionally, (CCW) materials can tolerate a pH range of 3 to 11 and temperatures from -32°C to 130°C [8]. These materials are composed of quartz sand, chemicals, cement in a powdery form, sodium silicates, metallic salts, and potassium silicates. When crystalline waterproofing interacts with the calcium hydroxide or calcium carbonates in the concrete, it forms calcium silicate hydrate (C-S-H) crystals, which fill the pores [9][10].

(CCW) materials can be applied in various ways, including as coatings or admixtures. A common application method is using rigid waterproofing materials, which involves pouring the (CCW) material directly into a fresh concrete mix. The self-sealing process is initiated once cracks form in the structure and water penetrates through the pores [11].

2. Methodology

In the first phase, the project began with a desk study that included the introduction, problem statement, objectives of the study, scope of the study, research significance, and literature review. This desk study was related to the project entitled Self-Healing Characteristics of Concrete Containing Capillary Crystalline Waterproofing Material.

Following the desk study, the raw materials that prepared were coarse aggregate, fine aggregate, ordinary Portland cement, water, and (CCW) material. The mix proportions were determined, which contributed to the next step which was the concrete mixture. During the concrete mixing process, data on the workability of the concrete were recorded. After the fresh properties were recorded, the concrete was cast and cured for 28 days.

Furthermore, each concrete cube was pre-loaded for crack self-healing purposes. A compression machine was used to pre-load the concrete cubes, and the curing continued until the end of 56 days, with compressive strength data being recorded.

In addition, the surface of each concrete cube was analysed for visual cracks, and samples were taken for scanning electron microscopy (SEM) analysis. Finally, all data were collected and analysed both theoretically and graphically.

2.1 Component of concrete

This subtopic explained about the raw material that use for these studies such as Portland cement, coarse aggregate, fine aggregate, (CCW) material, and water. Each of the raw material has bonding to each other in other to produce a great concrete design.

2.1.1 Portland Cement

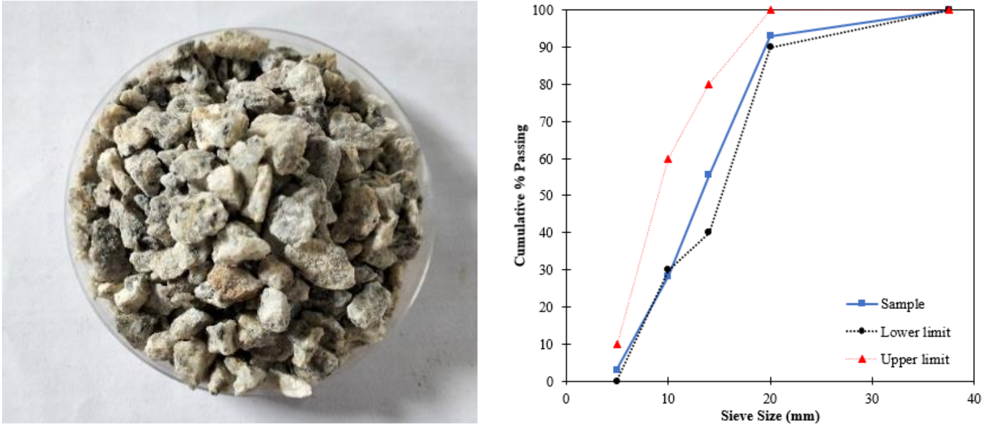
Cement one of important construction material that use in order to construct the concrete structure as shows in Fig. 1. However, the cement performance can be increase by additional admixture into the mixture design. According to [12] the stated that admixture have been found to significantly improve the performance of cement composites, which are widely used in the construction industry.

Fig. 1: Ordinary Portland Cement

The cement type that has been chosen in this study was the Portland Cement. This is because the reactions of carbonation and hydration reduce the volume of pore and smooth out the porosity mimicking the formation of the microstructure in the cement composites [13].

2.1.2 Coarse Aggregate

The natural coarse aggregate with size range of 5 mm to 10 mm used referred to Standard Specification for Building Works 2020 (JKR 20800-0226-20). Those coarse aggregate applied into the concrete mixture in order to increase the compressive strength of the concrete as shown in Fig. 2 (a). Provided that the maximum coarse aggregate size increase with a progressive quasi-static compressive strength [14]. Additionally, the rough surface of the coarse aggregate also helps into increase the compressive strength and tensile strength [15].



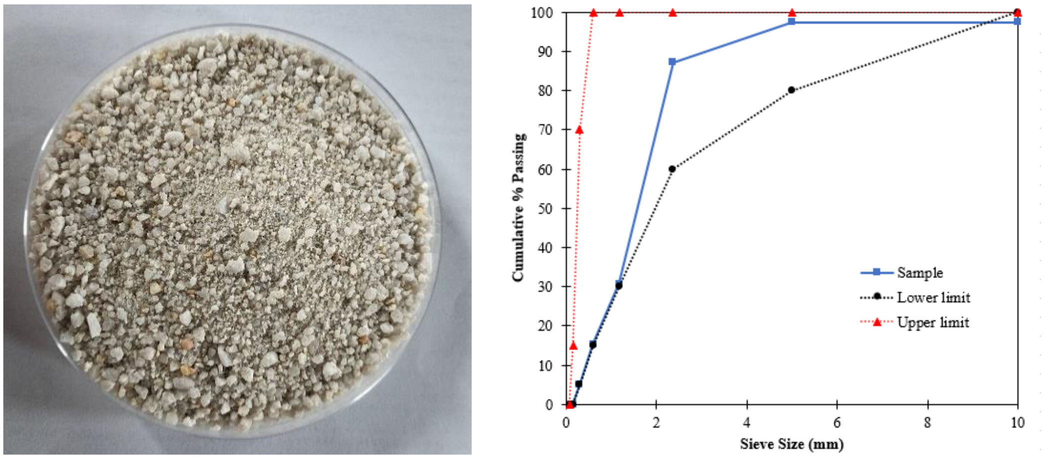
(a) (b)

Fig. 2: (a) Coarse aggregate (b) Coarse aggregate size distribution

According to the JKR standard for grading coarse aggregate, the coarse aggregate was tested by sieve analysis to determine the required size. The sieve sizes were based on The Standard for Test Sieves (BS410) for nominal sizes. The mass passing percentage for the size range of 5 mm to 10 mm was set at a minimum of 50% and a maximum of 85%, as shown in Fig. 2(b). The mass passing percentage was weighed and incorporated into the concrete mixture according to the specified mix proportion.

2.1.3 Fine Aggregate

Fine aggregate use into concrete mix in order to filled up the void between the coarse aggregate due to increase the bond strength. Fine aggregate sources such as crushed stoned, river sand, crushed gravel sand, and machine sand shows in Fig. 3(a). According to [16] explained that river sand is frequently utilized in concrete as fine aggregate. Referred to the JKR standard, the fine aggregate size range less than 5 mm used into the concrete mixture.



(a) (b)

Fig. 3: (a) Fine aggregate (b) Fine aggregate size distribution

The graph in Fig. 3(b) illustrates the size distribution of fine aggregates obtained through sieve analysis testing. According to the scope of the study, the selected fine aggregate sizes less than 5 mm. The graph indicates that the percentage passing for these sizes falls within the specified lower and upper limits.

2.1.4 Water

Fig. 4 shows the water used into concrete act as a bond of cement, coarse and fine aggregate together. Water one of element that use in concrete mixture in order to provide the hydration process with the cement paste. Water sources can be lake, ground water or rain water collection.

Fig. 4: Water

There were calculated approximately 16.6 km3 of water were used annually in the production of concrete [17]. Meanwhile for this project, the water-to-cement ratio used in this study was 0.5.

2.1.5 Capillary Crystalline Waterproofing Material

The (CCW) material shows in Fig. 5 is the admixture used in the concrete mix to provide the self-healing system. This (CCW) material is capable of protecting the concrete against water from external sources and soil.

Fig. 5: Capillary crystalline waterproofing material

As a result, the (CCW) material enhances the mechanical properties of the concrete. Research on the self-healing properties of cementitious crystalline waterproofing material under sulfate erosion has shown that cracks of up to 0.3 mm can heal, while in clean water, cracks ranging from 0.4 mm to 0.5 mm can be healed [18].

2.2 Preparation of concrete

In this subtopic, the writer was explained about the preparation of concrete from the design until the laboratory practice. In that case, the explanation starts from mix proportion, mixing, casting, and curing. The detail of the project design was explained in this subtopic.

2.2.1 Mix proportion

The concrete mix design with a ratio of 1:1.5:3 consists of 1 part cement, 1.5 parts fine aggregate, and 3 parts coarse aggregate to produce M25 grade concrete shows in Table 1 below. This mix design was applied for curing periods of 28 days and 56 days. Each batch sample consisted of 3 specimens for each mix proportion, resulting in a total of 36 specimens.

Table 1: Mix proportion by ratio method

% CCW Material	**Proportion in kg/m^3**			
	Cement	**Coarse Aggregate**	**Fine Aggregate**	**Water**
0.0	400	1200	600	200
0.5	400	1200	600	200
1.0	400	1200	600	200
1.5	400	1200	600	200

There are four variations of (CCW) material included in the concrete mix: 0%, 0.5%, 1.0%, and 1.5%. At the same time, pre-loading for crack initiation was set at 85%, 90%, and 95%, with corresponding compressive strengths of 21.3 N/mm^2, 22.5 N/mm^2, and 23.8 N/mm^2, respectively.

3. Result and Discussion

This chapter overview of the findings and analysis conducted for this project. Practical laboratory experiments were performed to collect the data necessary for achieving the study's objectives, including compressive strength tests, visual crack analysis, and Scanning Electron Microscopy (SEM) of the project samples. The collected data were analysed both graphically and theoretically to discuss the project's outcomes.

3.1 Fresh properties

Table 2 below shows the results from the slump test conducted for all the mix proportions. The slump test was performed to ensure that the concrete mix had the correct workability for the design requirements. Additional water was included in the mix because the coarse aggregate used was not of the Saturated Surface Dry (SSD) type.

Table 2: Result of slump test

Mix Proportion	**Slump Test (mm)**	**Additional Water**
Control	100	2% from weight of course aggregate
0.5% CCW	85	2% from weight of course aggregate
1.0% CCW	90	2% from weight of course aggregate
1.5% CCW	80	2% from weight of course aggregate

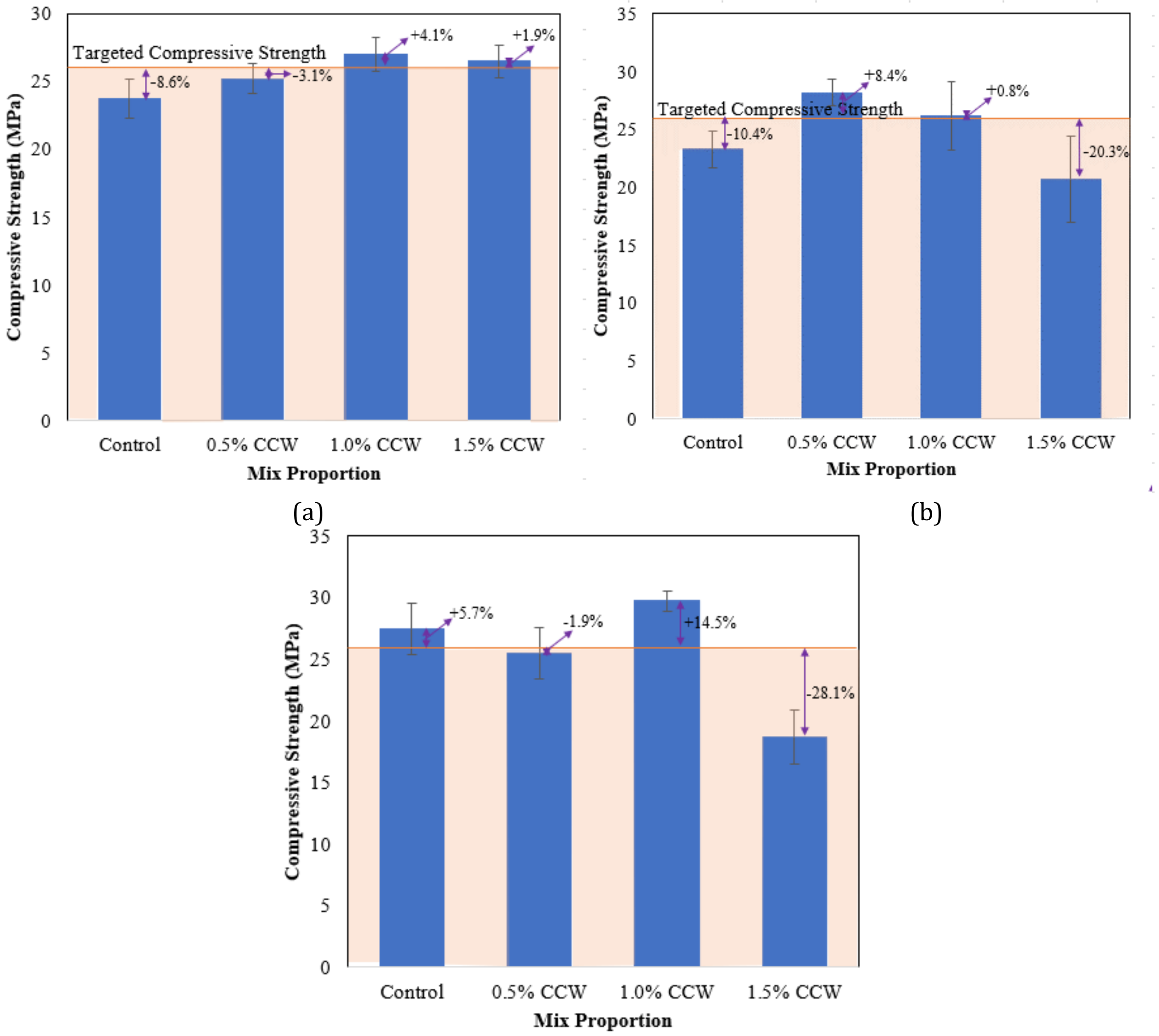
This was necessary to prevent the mix from becoming too dry, which could weaken the concrete's strength and lead to the formation of honeycomb. The added water helped maintain the desired consistency and ensured proper compaction during placement.

3.2 Compressive strength of concrete

Based on graph in Fig. 6 (a) shows the compressive strength in 56 days after pre-loading about (21.25 MPa) 85% from the grade of the concrete design which is 25 MPa. The mix proportion for Control was the control of the sample. The value of the compressive strength for mix proportion 1.0% CCW was higher than others which is 27.03 MPa. The compressive strength for mix proportion Control was the lowest value for this ratio which is 23.74 MPa. The mix proportion for 1.5% CCW and 0.5% CCW for compressive strength were 26.46 MPa and 25.17 MPa.

Based on graph in Fig. 6 (b) shows the compressive strength in 56 days after pre-loading about (22.5MPa) 90% from the grade of the concrete design which is 25MPa. The mix proportion for Control was the control of the sample. The value of the compressive strength for mix proportion 0.5% CCW was higher than others which is 28.16 MPa. The compressive strength for mix proportion 1.5% CCW was the lowest value for this ratio which is 20.70 MPa. The mix proportion for 0.5% CCW and 1.0% CCW for compressive strength were 28.16 MPa and 26.18 MPa.

Based on graph in Fig. 6 (c) shows the compressive strength in 56 days after pre-loading about (23.75 MPa) 95% from the grade of the concrete design which is 25 MPa. The mix proportion for Control was the control of the sample was 27.44 MPa. The value of the compressive strength for mix proportion 1.0% CCW was higher than others which is 29.73 MPa. The compressive strength for mix proportion 1.5% CCW was the lowest value for this ratio which is 18.68 MPa. The mix proportion for 0.5% CCW compressive strength was slightly low than Control which is 25.47 MPa.



(a) (b)

(c)

Fig. 6: Compressive strength at 56th day of specimen with : (a) 85% pre-loads; (b) 90% pre-loads; (c) 95% pre-loads

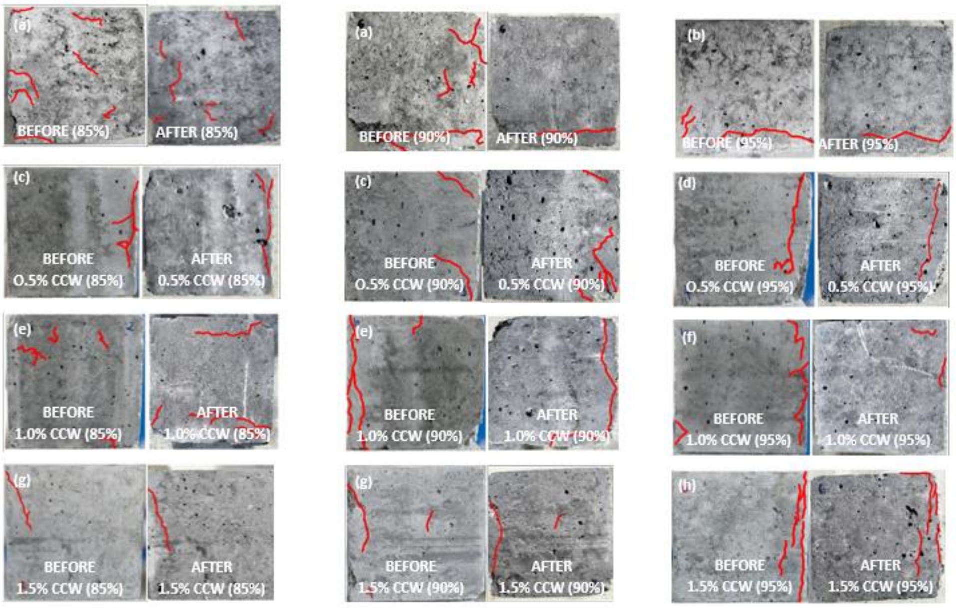
Hence, the compressive strength of concrete is a critical factor in construction projects, as it determines the building's suitability to withstand loads based on its intended function. The results presented are the compressive strength values after 56 days of pre-loading using a compression machine. The concrete was designed to achieve a grade of 25 MPa across all samples. The results showed compressive strength retention of 85%, 95%, and 90% from the concrete grade. The Control, 0.5% CCW, 1.0% CCW, and 1.5% CCW product inclusions, respectively.

3.3 Visual crack analysis

According to the comparison between Fig. 7(a) and 7(b) shows the visual crack analysis between 85% and 90% pre-loads. There are vary crack formation for each of the mix proportion. The control sample was the high crack pattern due no additional chemical inclusion for crack self-healing. The crack self-healing actively happens on mix proportion 1.0% (CCW) inclusion. This is because the proper filled cracks with the reaction with the free lime in the concrete cube and produce a crystal in capillaries. In addition, the inclusion 1.5% of (CCW) not showing any of self-healing characteristic for both pre-load condition. This is because the early hydration process may be slowed down or disrupted by overdosing (CCW), so causing delayed or insufficient strength development. In addition, the inclusion of 0.5% (CCW) shows the improper crack self-healing due to inadequate (CCW) product in the concrete. In that case, there would not be enough reactive compounds to create crystals that obstruct microcracks and capillaries. As a result, the concrete's ability to act as a waterproof material is diminished.

Next, comparison between Fig. 7(a) and 7(c) shows the visual crack analysis between 85% and 95% pre-loads. Each of the crack on the concrete cube has a variation of pattern that has been occurred. According to the table above, the inclusion of 0.5% (CCW) and 1.0% (CCW) shows that self-healing characteristic trend compare to the Control. This is because the concrete cube's free lime reacts with the properly filled fractures to form a crystal in the capillaries. For both pre-load conditions, 1.5% of (CCW) did not exhibit any self-healing characteristics. This is because taking too much (CCW) can slow down or interfere in the early hydration phase, which results in delayed or inadequate strength development. Then, there would not be enough reactive substances to form crystals that block capillaries and microcracks.

The different impacts of (CCW) admixtures on concrete durability are demonstrated by the examination of crack behaviour and self-healing capability under 90% and 95% pre-load circumstances in Fig. 7(b) and 7(c). There was no self-healing ability in the Control sample, as cracks remained severe and unhealed under both stress settings. With a discernible drop under 95% pre-load, the 0.5% (CCW) mix demonstrated limited healing performance, indicating its partial efficacy. The best self-healing ability was shown by the 1.0% (CCW) mix, which successfully sealed cracks in both pre-load scenarios. This suggests that by maximizing crystalline formation, the proper quantity of (CCW) improves concrete's capacity for self-healing. However, when it came to self-healing, the 1.5% (CCW) combination did the worst because overdosing on (CCW) decreased its efficiency, most likely because too much crystalline formation interfered with the healing process. According to the results, 1.0% (CCW) is the ideal mix fraction for improving self-healing and crack resistance, which makes it appropriate for applications needing strong, long-lasting concrete structures under high loads.



(a) (b) (c)

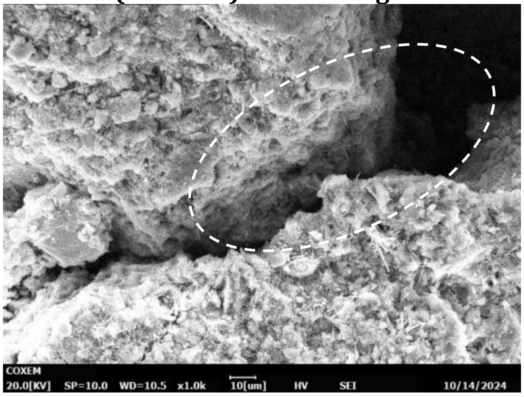
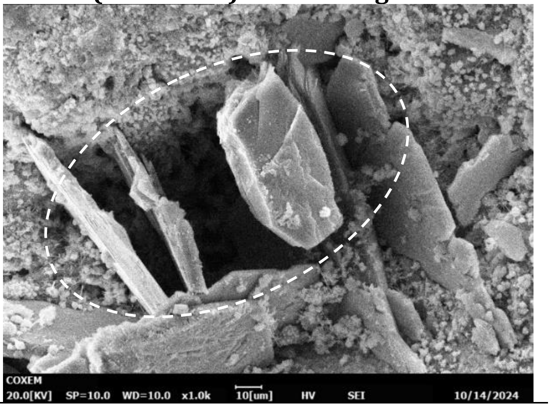
Fig. 7: Crack visual analysis before and after; (a) 85% pre-load; (b) 90% pre-load; (c) 95% pre-load

Crack visual analysis in this project was used in order to inspect the self-healing characteristic started from day 28 until day 56. The crack initiated by compression machine at days 28 due to matured concrete for the concrete cube. Each concrete cube has own crack pattern due to percentage of pre-loads. The compressive strength and crack were related due to percentage of porosity in concrete.

3.4 Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) one of ways to validate the morphology test on sample. The sample was scanning with high technology with high magnification to go through on the surface of the concrete. There are two sample was conducted with is Control and 1.0% (CCW) sample. The magnification up to 1000x for concrete sample to be scanned as presented in Table 3 for unfilled and filled cracks in concrete samples with and without (CCW) products.

Table 3: Unfilled crack and crack filled with CCW

Control (0% CCW)- 1000x magnification	**CCW (1.0% CCW)- 1000x magnification**
	

Due to the absence of any extra self-healing agents that would encourage crack sealing, the Control sample shows exposed cracks. The excess hydrated cement in the Control sample does not react with any chemical agents to form compounds like calcium silicate hydrate (C-S-H) or calcium carbonate ($CaCO_3$), which are necessary for self-healing, so the cracks stay unoccupied.

Compare to the 1.0% (CCW), the crack was filled due to the creation of chemical compounds such as calcium silicate hydrate (C-S-H) and calcium carbonate (CaCO3) is the primary cause of the self-healing property of concrete containing (CCW) products. (CCW) activates unhydrated cement particles when water seeps into cracks, creating more C-S-H that fortifies the concrete and plugs the fissures. Calcium carbonate, which fills and seals the fissures, is created when calcium hydroxide ($Ca(OH)_2$) combines with carbon dioxide. Together, these substances help concrete structures last longer, be more durable, and have smaller cracks.

4. Conclusion

According to the first objective of the project, which aimed to analyse the crack filling mechanism in concrete containing (CCW) material under varying loading magnitudes, the results were positively achieved. This is evident from the visual crack analysis data for the 85%, 90%, and 95% pre-load conditions, each showing different crack patterns. The crack sealing mechanism was observed, with the data collected before and after the tests showing positive results, indicating that the cracks were effectively filled by the (CCW) product.

The second objective, which aimed to determine the optimum inclusion of (CCW) in concrete with various crack formations, was also successfully achieved, as reflected in the compressive strength data. The optimum (CCW) inclusion was found to be 1.0% by weight of the ordinary Portland cement. This mix proportion exhibited the highest compressive strength, reaching 29.73 MPa under the 95% pre-load condition.

In a nutshell, (CCW) material is a vital product in today's globalized construction industry. Not only does it improve the aesthetic value of concrete, but it also enhances its durability and compressive strength, making it a valuable material for long-lasting and robust concrete structures.

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Conflict of Interest

Authors declare that there is no conflict of interest regarding the publication of the paper.

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