Enhancement of self-healing to mechanical properties of concrete

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Abstract. Concrete is the main construction material of many structures. Exposing to loads creates cracks in concrete, which reduce the performance and durability. The decrease of concrete cracks becomes a necessity demand to ensure more durability and structural integrity of the concrete structure. Autogenous healing concrete is a kind of new smart concretes, which has the ability to reclose its cracks by means of itself. Concrete self-healing is a type of free repairs processes, which is reduce direct and indirect cost of maintenance and repairing. This work targets to inspect the mechanical properties of concrete after using two combinations of two materials (20 kg/m3 calcium hydroxide Ca(OH)2 and 2 kg/m3 sodium carbonate Na2CO3 and 30 kg/m3 calcium hydroxide and 3 kg/m3 sodium carbonate) as a partial replacement of cement to work as self-healing agents. The paper reports and study the compressive, flexural and splitting tensile strengths and ultrasonic pulse velocity tests’ results at 7, 28 and 90 days of concrete age. Use of two combinations of calcium hydroxide and sodium carbonate, as healing agents, enhanced the mechanical properties of concrete and reduced the width of concrete cracks with time. The concrete compressive strength was increased after curing for 90 days by 9.3 and 11.1 %, respectively. The flexural strength was improved by 14.3 and 15.9 %, respectively. Also, the splitting tensile strength was enhanced by 6.9 and 9.3 %, respectively.

1. Introduction
Concrete cracks formulation works as a significant task in the reactions to loads in both compression and tension case. These cracks strongly effect service life of all the structures in contact with water and decrease the capability of concrete cover to shield steel reinforcement against corrosion [1].

Cracks width should not be more than specific limits. Serviceability limits of a concrete structure are largely controlled by spreads of the damages. Concrete cracks might become larger that threaten...
durability of the structure. So, the periodic checkup, maintenance, and repair of the concrete cracks are necessary. Yet, the repair of inner cracks is complicated [2].

Handling of the concrete cracks with a width of several hundred micrometers figures critical rehabilitation mechanism and performs an influential key role on the materials sustainable design [3]. When a small crack closes without any tangential displacement, it possibly will heal semi-completely in moister condition. The concrete crack resealed is defined as autogenous concrete healing process [4].

Concrete with self-healing has been considered as one of new and smart materials, in which their inner cracks and minor imperfections have the ability to be sealed without external involvement [5].

In 1836, the French Academy of Sciences was the first to notice the autogenous healing process of concrete cracks in structures retaining in water.

Edvardsen (1999) [6] gave details on the crystallization of the calcium carbonate in a cracked fracture surface and supposed that it was the major way for self-heal process of the cracked concrete.

One of the important factors that essentially affect the cracks self-heal process is the amount of water added to the concrete mix. Anhydrate cement particles may react with penetrated moisture through the crack causing to reclose it [7].

The concrete self-healing process can be expanded and accelerated by replacing a small amount of the cement or the sand with additives [5].

The autogenous healing process of young concrete cracks due to some additives and frequently periodic wetting and/or immersion can undergo widths in the range of 0.1 to 0.2 mm through several weeks [8].

Self-heal of concrete may be used to:
1- Concrete durability increases [9].
2- Restraint concrete cracks width and healing them quickly to prevent reinforcements corrosion [10].
3- Maintenance costs reducing.
4- Decrease demand to build new concrete buildings due to increasing service life of concrete structures.

The concrete with self-heal ability, caused by adding healing agents, researches initiated a new type of smart construction material [11].

In the present work, concrete mechanical properties including compressive strength, splitting tensile strength and flexural strength for all mixes (reference and with two types of the healing agents with different dosages) at 7, 28 and 90 days ages) were investigated. Also, ultrasonic pulse velocity (UPV) tests were done to check the recovering of cracked concrete compressive strength.

2. Experimental Work

Four basic concrete materials were used for reference mix, Ordinary Portland Cement, natural sand (Zone 3), natural gravel (Grade 5-20) and potable water. These materials were confirmed to specialized Iraqi Specifications (IQS No. 5/1984 [12] for cement, IQS No. 45/1984 [13] for aggregate and IQS No. 1703/2000 [14] for water). The healing agents, fine white powders supplied from a supplier, that used consisted of two materials (calcium hydroxide Ca(OH)₂ and sodium carbonate Na₂CO₃) as a partial replacement of cement.
The weights of the components in the concrete mix, to get a compressive strength of about 35 MPa, is given in Table 1.

Table 1. Weights of the components in the concrete mix according to [15].

| Material   | Cement (kg/m$^3$) | Gravel (kg/m$^3$) | Sand (kg/m$^3$) | Water (kg/m$^3$) |
|------------|-------------------|-------------------|-----------------|------------------|
| Mix proportion by weight | 456               | 1040              | 555             | 205              |
| Mix proportion      | 1                 | 2.281             | 1.217           | 0.45             |

The experimental program contains of casting three mixes. The healing agents’ weights in these three mixes are listed in Table 2. M1 represents the reference mix. Several trail mixes had been made to inspect the workability. The slump of all the mixes is within the range of 75-100 mm. The healing agents that used had been chosen based on works of [16], [17] and [18].

Table 2. Weights of healing agents in concrete mixes.

| Mix | Calcium Hydroxide (Ca(OH)$_2$) (kg/m$^3$) | Crystallization Material (Na$_2$CO$_3$) (kg/m$^3$) |
|-----|------------------------------------------|--------------------------------------------------|
| M1  | 0                                        | 0                                                |
| M2  | 20                                       | 2                                                |
| M3  | 30                                       | 3                                                |

For each concrete mix, three groups of samples were casted:

Group 1: to find the compressive strength of the concrete mix at 7, 28 and 90 days, 9 cubes with (100×100×100) mm were casted. The average of three cubes has been taken for each concrete mix. Also 30 cubes were casted to determine the self-healing of cracks that introduced due to compressive stresses and cured for 90 days.

Group 2: to find the flexural strength of the concrete mix at 7, 28 and 90 days, 9 prisms with (100×100×400) mm specimens were casted.

Group 3: to find the tensile strength of the concrete mix at 7, 28 and 90 days, 9 cylinders with (150×300) mm specimens were casted.

All tests on concrete specimens were done according to international standards (BS EN 12390-3 [19] for compressive strength, ASTM C293 / C293M-16 [20] for flexural strength and ASTM C496 / C496M-17 [21] for tensile strength) at ambient room temperature. ACI Committee 224R-09 [22] states that a cracking load (40% of the expected ultimate load) was chosen and the concrete cubes were compressed using (SANS) compression device of (600 kN) maximum capacity in the Department of Civil Engineering laboratories, University of Baghdad.

3. Results and Discussions

Figure 1-a presents the compressive strength tests results for the three concrete mixes at the three ages. From the first week, the increasing in the compressive strength was appeared slightly and continues to final age of test.

The test results indicated that compressive strengths of the self-healing concretes were higher than that of the normal concrete. The greatest increasing appears at age of 90 days that attributed to effect of healing agents. Table 3 presents the increasing percentages in compressive strength, flexural strength
and splitting tensile strength due to different content of healing agents compared to reference concrete mix.

Table 3. Percentage of increasing in compressive, flexural and splitting tensile strength.

| Mix  | Compressive strength | Flexural strength | Splitting tensile strength |
|------|----------------------|-------------------|----------------------------|
|      | Age (days)           | Age (days)        | Age (days)                 |
|      | 7                    | 28                | 90                         |
| M2   | 0.4                  | 0.8               | 9.3                        |
| M3   | 2.3                  | 2.3               | 11.1                       |

The increase in cement weight that replaced by healing agents increased the compressive strength of the concrete mix.

Figure 1-b presents flexural strength results for the three concrete mixes at the three ages. The results indicate that flexural strength of self-healing concrete is slightly higher than that of normal concrete at all ages of tests. This result is in agreement with the conclusions of [23].

Figure 1-c presents splitting tensile strength results for cylinders. The results show that the tensile strengths of self-healing concretes were slightly higher than that of the normal concrete at all ages of tests.

![Figure 1](image1.png)

Figure 1 Strength results (MPa) with age (a) compressive (b) flexural (c) splitting tensile.

The tests of UPV used to confirm the strength and the quality of concretes and provide data on the concrete properties [24]. UPV has been utilized to distinguish variations between the three concrete mixes that made in this work and determine weakening after cracking process and regaining of the concrete compressive strengths and micro cracks of the concrete cubes after curing. Thirty concrete cubes samples of (100×100×100) mm dimensions have been utilized to evaluate pulse velocities. The variations in UPV readings before and after applying compressive stresses indicate multi inner micro cracks formulations in the concrete. Figure 2 shows the results of ultrasonic pulse velocity for reference concrete (M1). They present that the readings decreased after applying compressive stresses due to inner micro cracks formulations. Later, and after curing for 90 days, the results show very slightly increasing in UPV readings. This was accredited to continuity in the cement hydration progression by hydration of the residue unhydrated cement.
Figures 3 and 4 show the results of ultrasonic pulse velocity for concrete mixes M2 and M3 respectively. The results of UPV after cracking are decreased and that indicates to the formation of micro cracks in the concrete cube, meanwhile the continuous curing for 90 days shows perceptible increases in UPV results, and this denotes to the regaining of the concrete compressive strength, and resealing of the concrete micro cracks result from the creations from self-healing reactions, and this in agreement with [25].

Figure 3. The values of UPV for concrete mix M2.

Figure 5 shows a comparison in the average UPV readings after 90 days from cracking for the three mixes. The results of UPV for concrete mixes M3 and M2 were more than that for concrete mixes M1, this means that amount of increases in the self-healing increases with the adding of the healing agents.
The amount of self-healing products increased with increasing period of curing, especially for the first month of curing, and continued to increase but at smaller rate, this is in agreed with [24] and [25]. This attributed for being the self-healing process principles are very similar to the principles of processes that occur during the hydration and hardening of concrete, so the self-healing reactions are relatively rapid at first time but it continues for long time [26].

The compressive strength was tested for the self-healed specimens in order to estimate the self-healing effects on the compressive strength. The results show recovering in compressive strength of self-healed specimens for all concrete mixes, as shown in Figure 6. A recovering was observed in concrete mixes M2 and M3, and that attributed to the effect of two healing agents’ materials in sealing the cracks and regain the integrity of cracked specimens. The incorporation of sodium carbonate leads to higher later strength due to relatively low solubility in the water [27]. The produced calcium carbonate gives finer
pore structures as well as reduction in the total pore volume and reduce the permeability of the concrete, also Calcium compounds enhanced compressive strength of the concrete samples, so the adding of Ca(OH)$_2$ was useful in terms of the concrete compressive strength [28].

![Compressive strength graph](image_url)

**Figure. 6** Recovering in compressive strength.

**Figure. 6** shows microscopic image for the self-healing effect (before and after) on micro cracks in a sample from concrete mix M3.

![Microscopic image](image_url)

**Figure. 7** Microscopic image for sample from concrete mix M3, (a) before healing (b) after healing.

### 4. Conclusions

From the experimental results obtained in the experimental work, the following conclusions can be listed:

1- Self-healing of the concrete cracks due to adding two healing agents (calcium hydroxide Ca(OH)$_2$ and sodium carbonate Na$_2$CO$_3$) was observed.

2- Test results showed that the compressive strength of the two self-healing concretes was higher than that of normal concrete after curing for 90 days by 9.3 and 11.1%, respectively. The increasing in the concrete compressive strength occurs somewhat in first week of age and continues to final age of tests.
3- The increase in the amount of the healing agents at the expense of the cement increased concrete compressive strength.
4- The results indicate that flexural strength and splitting tensile strength of self-healing concretes are slightly more than that of the normal mix at all ages.
5- The results of the UPV for concrete mixes with healing agents appear obvious compressive strength recovering than that for normal concrete.

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