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Evaluation of Strength Properties and Crack Mitigation of Self-healing Concrete

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ABSTRACT

Self-healing concepts are being adopted for the enhancement of durability of concrete and the extension of service life of concrete structures. Bio-mineralization is an eco-friendly bio-process, which shows promising results in sealing micro-cracks by Microbially-Induced $CaCO_3$ Precipitation (MICP). Introduction of specific bacteria into concrete with self-healing agent helps mediate MICP. Adopting greener alternatives and utilization of bi-products, such as fly ash which is used to prepare light-weight aggregates, reduces the demand for raw materials. A comparison between normal concrete and light-weight concrete is carried out to assess the ability of sealing cracks in concrete. Compressive strength, split tensile strength and crack width analysis were done for bacteria-based specimens. SEM and EDS analyses were also performed to investigate the calcite precipitation in concrete specimens and chemical deposition of bacterial concrete.

KEYWORDS: Light-weight concrete, Bacteria, SEM, Self-healing.

INTRODUCTION

Formation of tensile cracks leads to ingression of chemicals or water into the concrete. The renovation of buildings costs much; expensive renovations could be prevented by approaching self-healing techniques. To overcome such situations, adopting a novel self-healing technique can be used to prevent cracks in concrete. A realistic self-healing technique which was rapidly developing by mineral deposition can be achieved by incorporating bacteria as a healing agent into concrete. Bacteria-based self-healing technique is an eco-friendly bio-mineralization process which can be able to heal cracks formed in concrete without human interaction. When cracks appear, water finds its way into the concrete and activates the bacteria; therefore, precipitation takes place and this closes the cracks in concrete. *Bacillus pasteurii*, which is a common soil bacterium, rich in urease production, is adopted for the bio-mineralization process. The bacteria present in concrete remain dormant and activate when water ingresses into the formed cracks (Gandhimathi et al., 2012; Jing Xu, 2014). The mechanism behind this technique is the formation of calcium carbonate ($CaCO_3$) precipitation which can be defined as microbially-induced $CaCO_3$ precipitation (MICP).

Fly ash is an industrial by-product which is produced from thermal power plants. Such by-products are used as supplementary cementitious materials in construction industry, which reduces the disposal problems. Fly ash can be used to prepare artificial light-weight aggregates by cold bonding or pelletization process (Harilal, 2013). Light-weight aggregates can be used for production of

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light-weight concrete for attaining adequate strength. Light-weight concrete has a high bonding strength. It covers less volume in structures and gives similar strength compared to normal concrete. Reduced size in structural elements transfers less loads to the foundations. It also gives less weight-to-strength ratio for production of sustainable concrete (Niyazi Ugur Kockal, 2011; Gomathi, 2015).

The survival of bacteria in expanded clay aggregates was found to be sustainable and the EDS analysis had shown the presence of calcite deposition in the form of $CaCO_3$ precipitation in the concrete specimens. The visual inspection of healing the cracks proved that the bacteria suspended in water had survived and helped in the self-healing process (Jonkers et al., 2011). Split tensile strength of light-weight concrete is considered in the design criteria; so, split tensile strength of light-weight concrete is more concentrated on in this research. Healing of cracks is done in order to remediate the tensile cracks formed and the percentage of load after healing is taken. By comparing conventional bacterial concrete with light-weight bacterial concrete, an eco-friendly and effective biological sustainable concrete can be achieved.

Materials Used

53 grade Ordinary Portland Cement (OPC) with a specific gravity of 3.14 was used conforming with IS: 12269-1987 for the entire study. Locally available graded aggregates of 20 mm size were used conforming with IS: 383-1970. Natural river sand of zone III conforming with IS: 383-1970 was used. Class F fly ash was used for preparation of light-weight aggregates conforming with IS 3812.

Calcium lactate white powder material which is bought from a local chemical merchant was added in a percentage of 6% by weight of cement into the concrete mix. *Bacillus pasteurii* which is formerly known as *Sporosarcina pasteurii* is a common bacterium found in soil, producing urease. The bacterial pure culture strain was bought from the national collection of micro-organisms (NCIM), Pune.

Experimental Study

The concept of self-healing in both normal and light-weight bacterial concrete is to form $CaCO_3$ precipitation on the surface of the cracks. The ability to seal the cracks can be achieved by Microbially Induced $CaCO_3$ Precipitation (MICP). Calcium carbonate can be formed on the surface of the cracks by reacting with CO_2 present in the calcium hydroxide by the following reactions:

$$CO_2 + Ca(OH)_2 \rightarrow Ca\,CO_3 + H_2O \qquad (1)$$

$$Ca(C_3H_5O_2)_2 + 7\,O_2 \rightarrow CaCO_3 + 5\,CO_2 + 5\,H_2O \qquad (2)$$

This process is more efficient, because active metabolic conversions of calcium nutrients and bacteria are present in the concrete (Klaas van Breugel, 2012). The bacteria incorporated in the specimens for self-healing give rise to pH increase, resulting in the formation of carbonate ions.

$$Ca^{2+} + cell \rightarrow cell\text{-}\,Ca^{2+} \qquad (3)$$

$$Cell\text{-}Ca^{2+}\,CO_3^{2-} \rightarrow cell\text{-}\,Ca\,CO_3 \downarrow \qquad (4)$$

In the above equations, the cell wall of the bacteria is negatively charged; cations from the environment are drawn by the bacteria. Including Ca^{2+} ions to deposit on the cell surface, subsequent reaction with CO_3^{2-} -ions by Ca^{2+} -ions can be seen, leading to $CaCO_3$ precipitation at the cell surface (Wasim Khaliq, 2016).

Preparation of Bacterial Solution

The bacteria that should be added may be liquid (broth) or solid (agar). For the purpose of adding into concrete, the liquid form has been chosen. The bacteria to be added should be grown in specific media. The broth solution can be prepared by suspending 13.0 grams of nutrient broth in 1000 ml of distilled water and consists of ingredients, such as sodium chloride, beef extract, yeast extract and peptic digest of animal tissue. These ingredients act as food for bacteria in the concrete. The media were autoclaved at 121° C for 20 minutes.

Then, the bacterial pure culture was inoculated in a broth medium. The inoculated broth medium was kept in an incubation chamber at 37° C for 24-48 hrs.

Preparation of Light-weight Aggregates

Light-weight fly ash aggregates were prepared by the process of pelletization. Sprinkling water on a rotating pelletizer disc which contains 90% fly ash and 10% cement results in the formation of muddy balls. The pelletizer disc was kept at 45° angle and a rotating speed of 55 rpm. Class F fly ash has better binding property, since it contains CaO. The NaOH solution was used as binder at 5M mixed in water and sprinkled at the time of pelletization process. The freshly formed fly ash aggregates were kept for 24 hrs in room temperature for gaining initial strength and then allowed to cure in a hot air oven for 7 days at 100° C.

Light-weight Concrete

The mix design for light-weight concrete was adopted as per IS: 10262-2009 for M40 grade concrete. Light-weight concrete reduces the weight of concrete specimens. The unit weight was found to be 1810 kg/m^3. The allowable unit weight is up to 1900 kg/m^3 as per 213 R- Guide for Structural Light-weight Concrete. Average splitting tensile strength and compressive strength at 28 days were found to be 2.53 N/mm^2 and 31.7 N/mm^2, respectively. Table 3 of ASTM C 330- Guide for Light-weight Aggregates for Structural Concrete suggests that the 28-day average minimum splitting tensile strength is 2.2 MPa for 1760 kg/m^3 and the 28-day minimum compressive strength is 28 MPa for 1760 kg/m^3. The light-weight concrete specimens satisfy the ACI 213 R and ASTM C 330 standards.

Methods of Adding Bacteria into Concrete

The addition of bacteria into concrete for microbially-induced calcium carbonate precipitation (MICP) can be achieved in two ways:

Direct Addition

In direct addition, we add the bacteria into the concrete directly at the time of mixing. The healing agent was mixed with cement and added to the concrete to achieve better concrete pore structure. This direct addition process can be adopted for preparing normal bacteria-based self-healing concrete (Wasim Khaliq, 2016).

Encapsulation by Light-weight Aggregates

Encapsulation of concrete by replacing normal aggregates with light-weight aggregates can be carried out by immersing the light-weight aggregates into the bacterial solution. The major advantage of this encapsulation process was to achieve the sealing of internal cracks in the concrete. The bacteria are suspended in water as prepared with nutrient broth media. Light-weight aggregates are immersed into the bacterial solution for spore formation. After immersion, light-weight aggregates were allowed to cure for 24 hours in the bacterial solution. Then, the light-weight aggregates were used for casting light-weight concrete.

RESULTS AND DISCUSSION

Compressive Strength Test

Concrete specimens of 100x100x100 mm were cast and allowed to harden for different ages like 7,14,28,56 and 90 days. The specimens were loaded in a compressive testing machine for maximum load. Average compressive strengths for normal and light-weight concrete specimens are shown in Fig. 1. A gradual increase in compressive strength can be seen in both normal and light-weight concretes. Fly ash has attained strong bonding between aggregates and cement paste. This helps in developing a bridging between the internal cracks formed. Similar to compressive strength, increased internal bonding strength and better workability can be observed in light-weight concrete produced when compared to normal bacterial concrete.

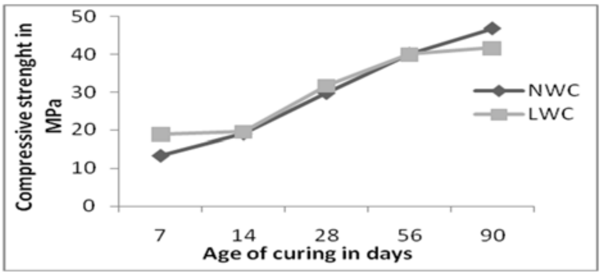

Figure (1): Compressive strength for normal and light-weight concrete

Ultrasonic Pulse Velocity Test

Ultrasonic pulse velocity test was conducted as per IS: 13311 on the concrete specimens of 100x100x100 mm size at different ages of curing in order to determine the quality of concrete. For normal bacterial concrete specimens, it can be seen that the quality of concrete achieved was good at 14 days of curing. As for light-weight bacterial concrete, the quality of the concrete is good at 28 days of curing. The average ultrasonic pulse velocity values for normal light-weight concrete specimens at different ages can be seen in Fig. 2.

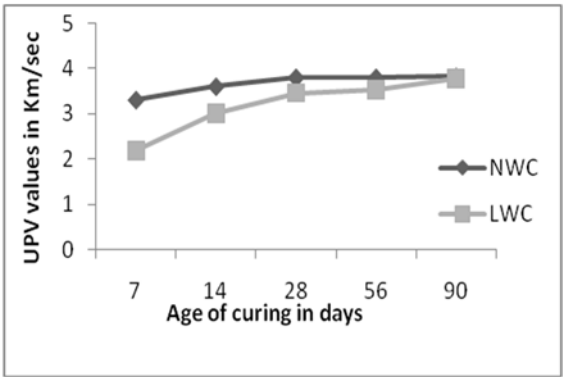

Figure (2): UPV values for normal and light-weight concrete

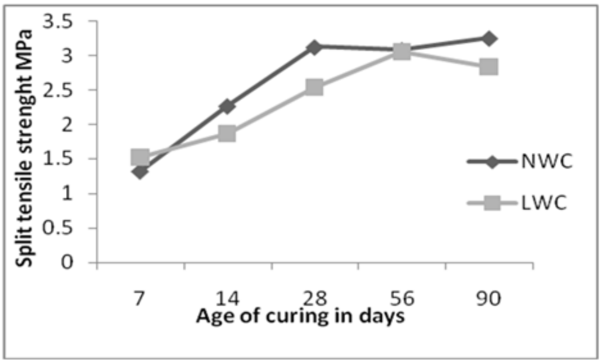

Figure (3): Split tensile strength for normal and light-weight concrete

Split Tensile Strength

Split tensile strength test was conducted on concrete cylinder specimens of 100 mm diameter and 200 mm depth at different ages of curing. The specimens were kept horizontally in order to create tensile cracks. load was applied and at the first failure, the specimen was taken out and allowed for curing in water for self-healing observation. The average split tensile strength values for normal and light-weight bacterial specimens shown in Fig. 3.

After 56 days of curing of the cracked specimens, the healed specimens were again tested for split tensile strength as shown in Table 1. 51% and 54% of the load were taken by normal and light-weight bacterial specimens, respectively after 56-day healing of cracked specimens as shown in Table 1. Light-weight bacterial concrete showed better results in terms of tensile strength by encapsulation of bacteria inside the light-weight aggregates. The internal healing of the light-weight concrete specimens can be seen by SEM investigation of light-weight aggregates present in light-weight concrete. Comparing both types of bacterial specimens, light-weight concrete showed better healing ability to seal the internal and external cracks formed in the concrete.

Table 1. Split tensile strength of cracked specimens at 56 days

S.No.	NWC (N/mm^2)	LWC (N/mm^2)
1	1.71	1.27
2	1.78	1.52
3	1.62	1.40
4	1.30	1.46

Crack Width Analysis

The approximate crack widths for normal and light-weight bacterial concrete specimens have been determined by using digimizer software. By visual inspection of the specimens, healing can be observed. By using digimizer software, the approximate crack widths and mean values of cracks can be observed. The cracks before and after healing in normal bacterial concrete specimens are shown in Fig. 4, while Fig. 5 shows the cracks before and after healing in light-weight bacterial concrete specimens.

Figure (4): Crack widths in normal bacterial concrete before and after 56 days of healing

Cracks approximately up to 0.5-0.6 mm were healed for normal bacterial concrete at the age of 56 days of curing. For light-weight bacterial concrete, approximately 0.6-0.7 cracks were healed. Visual inspection of healing ability of the bacterial specimens shows the healing capacity of the cracks. Light-weight concrete specimens show adequate formation of $CaCO_3$ on the cracks. The healing of cracks was achieved in both the types of bacterial concrete, where light-weight concrete shows better healing in sealing the cracks.

Figure (5): Crack widths of light-weight bacterial concrete before and after 56 days of healing

Scanning Electronic Microscopy (SEM)

Scanning electronic microscopic (SEM) images were taken for normal and light-weight bacterial specimens to check the $CaCO_3$ precipitation on the surface of the cracks formed. SEM images revealed that $CaCO_3$ precipitation is rich in light-weight concrete when compared to normal bacterial concrete as shown in Fig. 6 and Fig. 7.

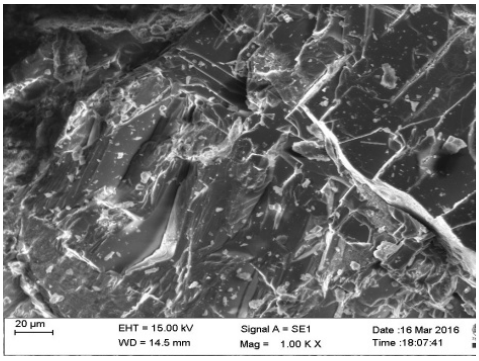

Figure (6): Formation of $CaCO_3$ on normal bacterial concrete specimens

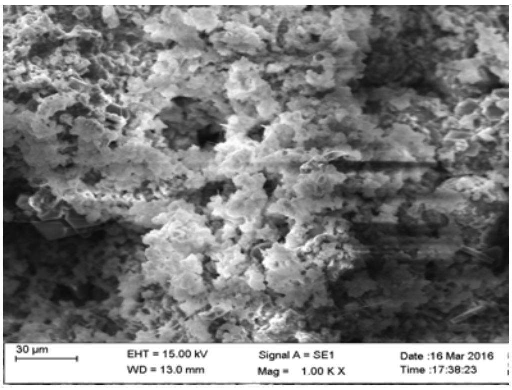

Figure (7): Formation of $CaCO_3$ on light-weight concrete specimen

EDS Analysis

Energy-dispersive X-ray spectroscopic (EDS) analysis has been conducted for concrete specimens in order to determine the chemical characteristics of the minerals formed in the cracked specimens. EDS anlysis confimed the deposition of calcium compunds in the concrete specimens. The chemical compositions present in the cracked specimens are shown in Fig. 8 and Fig. 9 for normal and light-weight bacterial specimens, respectively.

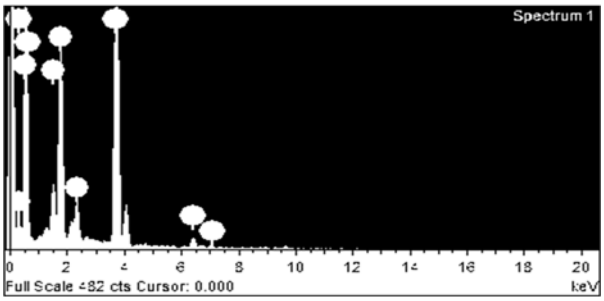

Figure (8): EDS spectrum of minerals deposited in normal bacterial concrete specimens

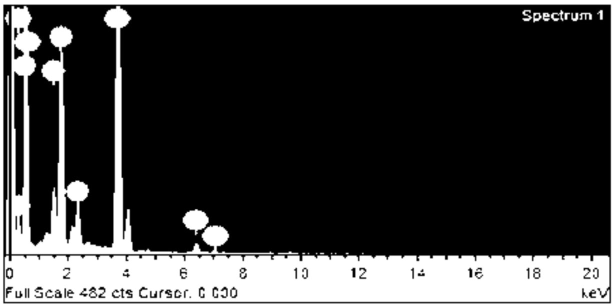

Figure (9): EDS spectrum of minerals deposited in light-weight bacterial concrete specimens

The EDS analysis revealed that the calcium deposit present in both the concrete specimens is due to formation of $CaCO_3$ on the surface of the cracked specimens. Compared to normal bacterial concrete, the $CaCO_3$ deposition was more in light-weight concrete specimens. This analysis was also carried out for light-weight aggregates to check the capacity of aggregates in forming the $CaCO_3$ on the aggregates which helps in internal healing and bonding of the concrete.

CONCLUSIONS

Based on the experiments, the following conclusions were drawn:

- An increase in tensile strength of around 50% occurred after the specimens were subjected to healing process.
- Normal concrete and light-weight bacterial concrete increase in tensile strength was 51% and 54%, respectively; thus, light-weight bacterial concrete has proven to be more effective than normal bacterial concrete.
- Visual examination and UPV transmission tests have proven the efficiency of biological treatment of concrete by bonding between the cracks. Light-weight bacterial concrete shows better healing, as strong bonding between the aggregates helps in healing of internal cracks formed. Complete sealing and better healing of cracks was observed.
- Cracks of widths of 0.24 mm, 0.34 mm and 0.5 mm were completely sealed in normal bacterial concrete. Cracks of widths of 0.36 mm, 0.45 mm, 0.547 mm and 0.6 mm were completely sealed in the case of light-weight bacterial concrete.
- The enriched calcium source helps in remediating the cracks by spore forming of bacteria embedded in light-weight aggregates as confirmed by EDS analysis. SEM investigation revealed the healing of cracks by $CaCO_3$ precipitation incorporating with bacteria and healing agent.

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