Strength Enhancement of Mortar using Biocementation Technique

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Abstract: Biocementation is a technique in which calcium carbonate (CaCO₃) gets deposited with the help of ureolytic bacteria. In this study, an attempt has been made to augment the properties of mortar utilizing bacterial solution made with soil bacteria and other nutrients. The consequence of bacterial solution was noticed in two methods. In the first method the bacterial solution is used in preparing the bacterial mortar specimens and in the second method the bacterial solution is used in surface treatment of mortar. Considerable enhancement of 20.08% in compressive strength and 10.52% decrement in water absorption of bacterial mortar over conventional mortar was observed at the end of 56 days of curing period.

Key words: Bacterial solution, compressive strength, water absorption, bacterial mortar, urease.

1. Introduction

Cementitious materials like mortar, concrete etc., are extensively used. These materials are vulnerable and lead to the pores formation by the exposure of hot weather, thereby making it permeable and leading to the formation of cracks in the cementitious materials [1-3]. Various commercial products are used such as surface coating, water Repellents, chemical admixtures, wide range of structural epoxy and synthetic filler agent are used to augment the durability of structure [1].

Although this conventional technique is effective, but they have sustained drawbacks such as constant maintenance, degradation over a period of time, cost, etc., so there is a necessity to provide an effective long term and efficient technology in order to enhance the mechanical performance of the composite material [2]. The basic metabolism induced by the bacteria is the precipitation of calcium carbonate [4].

According to S.A.Abo-El-Enein et al, the biologically induced cement-based material outperformed conventional concrete in terms of durability and crack repair. In this the biocementation has improves the mechanical properties of cement mortar [2].

Ghosh et al., enlighten the process of biomineralogy in mortar and concrete by using an anaerobic thermophilic shewanella species. Around 22.62% and 19% enhancement in 28 days compressive strength of concrete and mortar respectively was found at cell concentration of 10⁵ cells/ml, when compared to control specimens [3]. One more study was carried out by De Muynck et al. where mortar specimens treated with Bacillus sphaericus were found more resistant towards carbonation than untreated specimens. Also, treated samples were more durable showed about 65 to
90% diminution in water absorption depending on the porosity of specimens when compared to untreated specimens [5].

De Muynck et al., studied the effect of Bacillus sphaerius effect on the precipitation of calcium carbonate. Also, the effect of CaCO₃ precipitation developed by Bacillus sphaericius on performance of concrete was studied. The bio-depositions on the surfaces of mortar and concrete were seen to cause reduction in capillarity and air permeability [6]. Ghosh et al., studied the effect of facultative anaerobic Shewanilla species when incorporated in mortar. It was observed that there was a deposition of calcium aluminium silicate or gehlenite which is responsible for improving the compressive strength and also modifies the pore size distribution. It was also found that shewanella species secretes protein which has an ability to augment the strength of mortar [7].

Bacteria were protected from high pH in concrete by silica gel which also assisted CaCO₃ precipitation. Reduction in water permeability was observed in the study. The 16 capability of Bacillus sphaericius to precipitation calcium carbonate was analysed by thermo gravimetric method [8]. Crack healing capabilities of spore-forming Bacillus genus were explored. Bacillus subtilis were used in concrete. Authors concluded that bacteria from the class Bacillus exhibited the encouraging results in healing the cracks in concrete and also in increasing the durability of cement-based materials [9].

De Muynch et al. explore the role of biocementation in various fields of civil and geological engineering. Biocementation technique showed a positive potential to increase compressive strength and to heal cracks in the building materials. Large numbers of pores in sand were plugged due to CaCO₃ precipitation, thus decreasing the porosity [10]. Vempada et al. examined capability of bacteria to ameliorate the compressive strength by MICP. In this study, aerobic alkaliophilic bacteria such as Bacillus subtilis JC3 and salinicoccus sp is used. Bacillus Subtilis JC3 at cell concentration of 10⁵ cell/ml offered substantial improvement of 19.26% at 28 days of curing in compressive strength of cement mortar [11]. Bacillus subtilis when used concentration of 10⁷cells/ml showed the promising augmentation in compressive strength as well as crack healing [12].

A homogeneous MICP bonded bio-sandstones using sporosarcina pasteurii for historical conservation. It was concluded that sporosarcina pasteurii have the ability to develop CaCO₃ and can be efficiently used to conserve historical monuments [13]. The specimens treated with bacteria showed a considerable improvement in compressive strength and significant reduction in permeability [14]. Studies have been carried out where bacterial solution was prepared with rhizospheric soil and used in the cementitious materials, showed the promising results in terms of mechanical and durability parameters [15-18].

Generally, in conventional bio-cementation process isolated ureolytic bacteria are used along with the commercially available nutrients which make the process expensive. The study focused on improving performance of mortar utilizing bacterial solution made with soil bacteria (without isolation) and other naturally available nutrients. The use of ureolytic bacteria from soil in biocementation has become a popular technology for self-healing cementitious materials. The various biochemical reactions result in the formation of calcium carbonate, as shown in Eqn. (1) – (7)

As urea is hydrolyzed in the existence of urease, carbamate and ammonia are formed.

\[
\text{CO(NH}_2\text{)}_2 + \text{H}_2\text{O} \rightarrow \text{NH}_2\text{COOH} + \text{NH}_3 \quad (1)
\]
\[
\text{NH}_2\text{COOH} + \text{H}_2\text{O} \rightarrow \text{NH}_3 + \text{H}_2\text{CO}_3 \quad (2)
\]
\[
\text{H}_2\text{CO}_3 \rightarrow \text{H}^+ + \text{HCO}_3^- \quad (3)
\]
\[
2\text{NH}_3 + 2\text{H}_2\text{O} \rightarrow 2\text{NH}_4^+ + 2\text{OH}^- \quad (4)
\]
pH is increased as a byproduct of the above reactions, and the bicarbonate equilibrium changes, leading to the formation of carbonate ions.

\[
\begin{align*}
\text{HCO}_3^- + \text{H}^+ + 2\text{NH}_4^+ + 2\text{OH}^- & \rightarrow \text{CO}_3^{2-} + 2\text{NH}_4^+ + 2\text{H}_2\text{O} \\
\text{Ca}^{2+} + \text{Cell} & \rightarrow \text{Cell}-\text{Ca}^{2+} \\
\text{Cell}-\text{Ca}^{2+} + \text{CO}_3^{2-} & \rightarrow \text{Cell}-\text{CaCO}_3 \downarrow
\end{align*}
\]

(5)  
(6)  
(7)

2. Materials

2.1. Cement

53 grade Ordinary Portland cement (OPC) as per IS 12269-1987 is used [19]. Fineness, specific gravity, normal consistency and setting time tests of the cement were calculated according to IS 2386-3 1963, IS 4031-4 1988) [20, 21]. The before mentioned properties were given in table 1.

| Table 1. Physical properties of OPC |
|-------------------------------------|
| Properties                      | Test Results |
| Specific gravity                 | 2.95         |
| Fineness of cement               | 5%           |
| Standard consistency             | 30%          |
| Initial setting time             | 35 min       |
| Final setting time               | 600 min      |

2.2. Fine aggregates

In the preparation of mortar according to IS 383, 1970 [22], Zone II River sand has been utilised as a fine aggregate. Fineness modulus, water absorption, specific gravity, bulk density of loosen sand and bulk density of compacted sand were calculated (according to IS 2386-3 1963) [20]. The above said properties are represented in table 2.

| Table 2. Physical properties of fine aggregates |
|-----------------------------------------------|
| Physical properties                           | Values       |
| Specific gravity                              | 2.60         |
| Fineness modulus                              | 2.80         |
| Water absorption                              | 3.40         |
| Bulk density of loosen sand                   | 1428 kg/m³   |
| Bulk density of compacted sand                | 1624 kg/m³   |

2.3. Tap water

In this study the normal tap water is used according to IS 456-2000 [23].

2.4. Preparation of bacterial solution

Bacterial solution was prepared using soil bacteria and other natural nutrients for the growth of bacteria. Soil from the garden of VR Siddhartha Engineering College was taken as the source of bacteria. For bacterial growth, nutrients like lentil seed powder, sugar and kitchen wastewater were used as a protein source, carbon source and vitamin source respectively. Regular tap water was used for making the bacterial solution. The proportions of ingredients used in the making of bacterial
solution are given in table 3. After mixing these ingredients the solution was incubated at 37° for 24 h. To measure the growth of the bacteria, optical density of bacterial solution was observed by spectrophotometer at 600nm and it was found to be 0.1. The urea for urea hydrolysis as a substrate and Ca(OH)₂ as calcium source was used in order to carry out the biocementation process.

| Ingredients                  | Quantity |
|------------------------------|----------|
| Soil                         | 200 g/l  |
| Lentil seed powder           | 6 g/l    |
| Sugar                        | 1 g/l    |
| Kitchen wastewater           | 20 ml/l  |
| Urea                         | 6 g/l    |
| Calcium hydroxide            | 12 g/l   |

Table 3. Proportion of ingredients used in the preparation of bacterial solution

3. Methods

The effect of utilizing bacteria in mortar was observed in two different ways.

- Use of bacterial solution for the preparation of mortar specimens.
- Surface treatment of mortar using bacterial solution.

3.1. Preparation of specimens

Mortar was prepared with cement and sand ratio of 1:3 and W/C ratio of 0.45 was maintained. Cubes of size 70.7mm were prepared (according to IS: 4031, part 6, 1988) [24] and curing period 7, 28, 42, and 56 days were adopted.

3.2. Use of bacterial solution for the preparation of mortar specimens

In this method control mortar specimens and bacterial mortar specimens were prepared. The bacterial mortar specimens were prepared using bacterial solution and the mechanical properties were observed. The detailed preparation of specimens is given in table 4. Both control and bacterial specimens were cured by using tap water 7, 28, 42, and 56 days at room temperature.

Table 4. Preparation of mortar specimens

| S.no | Type of specimen            | Preparation of specimens               |
|------|-----------------------------|----------------------------------------|
| 1.   | Control specimens           | Cement, sand, tap water                |
| 2.   | Bacterial specimens         | Cement, sand, bacterial solution       |

3.3. Surface treatment of mortar using bacterial solution

In this method surface treatment was carried out using bacterial solution. The control and control I specimens were prepared. The bacterial solution was used as a curing. The control and control I specimens were cured in water and bacterial solution respectively. The curing span of 7, 28, 42 and 56 days were adopted. The detail preparation and curing conditions as mentioned in table 5.
Table 5. Preparation of mortar specimens

| S.no | Type of specimens       | Preparation of specimens       | Curing                  |
|------|-------------------------|--------------------------------|-------------------------|
| 1.   | Control specimens       | Cement, sand, tap water        | Tap water               |
| 2.   | Control I specimens    | Cement, sand, tap water        | Bacterial solution      |

4. Results and Discussion

4.1. Compressive strength

All the mortar specimens were tested under compressive strength test which is carried out according to IS 4031 (part 6) 1988 [24]. When the bacterial solution was used in preparing the bacterial mortar specimens it showed an average increase of 6.05%, 13.32%, 16.52% and 16.6% for 7, 28, 42 and 56 days of curing in compressive strength as compared to control specimens as mention in table 6 and shown in fig. 1. While, the bacterial solution when used as a curing solution for control and control I specimens exhibited an average increase of 15.85%, 19.02%, 20.08% and 20.42% for 7, 28, 42 and 56 days of curing period respectively as mention in table 7 and also shown in fig. 2.

4.2. Water absorption test

The test was performed according to ASTM C 140 [25]. It was observed that, when the bacterial solution was used in preparation of bacterial specimen the water absorption capacity was decreased by 14.31%, 15.32%, 18.16% and 20.68% for 7, 28, 42 and 56 days of curing span in bacterial specimens when compared to control specimens as mention in table 8 and shown in fig. 3. When the bacterial solution was used in surface treatment (as a curing solution) showed the reduction of 6.22%, 8.66%, 10.32% and 10.52% for 7, 28, 42 and 56 days respectively as mention in table 9 and shown in fig. 4.

Table 6. Compressive strength (MPa) of control and bacterial mortar specimens

| S.no | Days | Compressive strength MPa | % Increment |
|------|------|--------------------------|-------------|
|      |      | Control specimens        | Bacterial mortar specimens |         |
| 1.   | 7    | 24.6                     | 26.2        | 6.50       |
| 2.   | 28   | 53.03                    | 60.21       | 13.32      |
| 3.   | 42   | 55.23                    | 64.37       | 16.54      |
| 4.   | 56   | 56.15                    | 65.47       | 16.6       |

Table 7. Compressive strength (MPa) of control and control I specimens

| S.no | Days | Compressive strength MPa | % Increment |
|------|------|--------------------------|-------------|
|      |      | Control specimens        | Control I specimens (cured in bacterial solution) |
| 1.   | 7    | 24.6                     | 28.5        | 15.85      |
| 2.   | 28   | 53.03                    | 63.12       | 19.02      |
| 3.   | 42   | 55.23                    | 66.32       | 20.08      |
| 4.   | 52   | 56.15                    | 66.62       | 20.42      |
Fig. 1 Compressive strength (MPa) for control and bacterial mortar specimen. Standard deviation (n±5).

Fig. 2 Compressive strength (MPa) for control and control I specimens (cured in bacterial solution). Standard deviation (n±5).
Table 8. Water absorption (%) for control and bacterial mortar specimens

| S.no | Days | Water absorption (%) | % Reduction |
|------|------|----------------------|-------------|
|      |      | Control specimens    | Bacterial mortar specimens |            |
| 1.   | 7    | 4.82                 | 4.13        | 14.31       |
| 2.   | 28   | 4.96                 | 4.20        | 15.32       |
| 3.   | 42   | 5.23                 | 4.28        | 18.16       |
| 4.   | 56   | 5.51                 | 4.37        | 20.68       |

Fig. 3 Water absorption (%) for control and bacterial specimens. Standard deviation (n±5)

Table 9. Water absorption (%) of control and control I specimens

| S.no | Days | Water absorption (%) | % Reduction |
|------|------|----------------------|-------------|
|      |      | Control specimens    | Control I specimens (cured in bacterial solution) |
| 1.   | 7    | 4.82                 | 4.52        | 6.22        |
| 2.   | 28   | 4.96                 | 4.53        | 8.66        |
| 3.   | 42   | 5.23                 | 4.69        | 10.32       |
| 4.   | 52   | 5.51                 | 4.93        | 10.52       |
4.3 Scanning Electron Microscopy

For both control mortar specimens and bacterial mortar specimens, the scanning electron microscopy test was carried out after 56 days of curing period. Formation of CaCO$_3$ crystals in the bacterial mortar specimens was observed as shown in fig.5. The presence of voids is more in control specimens as compared to the bacterial mortar specimen this is due to the deposition of CaCO$_3$ carried out by ureolytic bacteria.

Fig. 5: Scanning electron microscopy for A) control mortar specimen and B) bacterial mortar specimen

The augmentation in compressive strength and decrement in water absorption was observed because of the deposition of CaCO$_3$ in the matrix of mortar. The bacterial solution when used in surface treatment i.e. used as a curing solution showed an encouraging result as compared to when used in preparing of bacterial mortar specimens. The use of natural nutrients over the commercially available nutrients.
5. Conclusion

Use of ureolytic soil bacterial solution in order to improve the properties of cementitious materials proved to be an effective technique. In this study, use of natural nutrients for the growth of bacteria resulted to be very cheaper as compared to commercial nutrients. It was found that there was a significant improvement in compressive strength and reduction in water absorption of control I and bacterial specimens for 56 days of curing period. Thus, this biocementation process has proved to be an efficient method to overcome the drawbacks of the conventional methods.

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