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Influence of nutrient components of media on structural properties of concrete during biocementation

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HIGHLIGHTS

- Nutrients retarded setting property of cement paste and decreased compressive strength of concrete.
- No impact on setting property of cement paste when admixed with bacterial culture.
- Compressive strength increased and permeability reduced with bacterial treated concrete.
- No significant variation in pH from bacterial treated and control specimens.
- Biogenic precipitation of $CaCO_3$ by bacteria counteract the retarding effect of organic nutrients.

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ABSTRACT

Application of microbial induced carbonate precipitation in cement-based materials has become substantially popular. In the present investigation, effect of nutrient components of media such as carbon and nitrogen content of organic nutrients and bacterial cells on the chemical and structural properties of concrete were studied. The retarding effect of organic nutrient medium on setting property of cement paste and decrease in compressive strength of concrete was observed. However, no impact on setting property of cement paste admixed with bacterial culture was observed. Significant increase in compressive strength and reduction in permeability was observed with bacterial admixed and surface treated concrete specimens. Carbon and nitrogen content were significantly increased in bacterial treated specimens compared to control. No significant variation in pH was observed from the samples collected from different depths of the concrete specimens both in bacterial treated and control specimens. Present study results suggested that biogenic precipitations of $CaCO_3$ by bacterial cells counteract the retarding effect of organic nutrients of concrete and enhance the durability properties.

1. Introduction

Concrete is the most important element of infrastructure development across the globe. Rapid growth in infrastructure has resulted into enhanced use of concrete as a construction material. With the increasing population, the demand for residential buildings, transport connectivity and industrial units has been escalated. After the start of industrial era, concrete has become the most widely used construction material. The incomparable property of concrete like high compressive strength, durability under aggressive environments, ability to be moulded into different shapes etc. has made it attractive among other construction materials. However, concrete is not free from severe degradation problems. The external attacks on concrete like chloride ingress, sulfate ingress and carbonation of concrete due to increasing level of carbon dioxide around its surrounding environment are matter of concern [1]. These external environmental attacks on the concrete structures are causing irreversible changes in its serviceability. The ingress of aggressive agents into concrete indicates the importance of permeation properties of surface layer of concrete [2,3]. Researchers had investigated the use of different treatments to refine the pore structure of concrete and to prevent the premature deterioration of concrete structures from the aggressive environment. Surface treatments like epoxy coatings, pore blockers, silanes, acrylic coatings etc., are available but these treatments are subject to frequent controversy due to their limited long-term performance, need for constant maintenance, cost, site accessibility and environmental impact [4].

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With time, microbially induced calcium carbonate precipitation (MICP) using calcifying bacteria has emerged as a promising technique in the field of concrete research. Initial applications of MICP include archeological stone restoration [5–7], soil strengthening [8] etc. During the last decade, the potential of calcifying bacteria in concrete has also been explored by researchers. The use of MICP in enhancing both strength and durability of concrete is investigated by various researchers [9–12]. The combined effect of precipitation of calcium carbonate by ureolytic bacteria in increasing compressive strength and reducing porosity of concrete has given the edge to biogeotechnology over other conventional techniques. Lab-scale experiments to remediate cracks in concrete had also shown promising results in which polyurethane embedded bacteria [9], silica gel immobilized bacteria [13], hydrogel encapsulated bacteria [14] were used to remediate cracks in concrete. Calcium carbonate crystals precipitated by bacteria resulted as a crack healing material which results into decreased water permeability.

The civil oriented research with microbial precipitation has focused on the use of ureolytic bacteria. These bacteria hydrolyze urea by producing urease enzyme in large amount resulting into release of ammonia and carbon dioxide. The ammonia produced increases the pH in the surrounding of bacteria that leads to precipitation of calcium carbonate [15]. Bacteria were supplemented with calcium source (i.e. calcium chloride) along with urea which results into the formation of calcium carbonate crystals with different morphologies like calcite, aragonite and vaterite. The biochemical reaction resulting from urea and $CaCl_2$ medium on the negatively charged cell surface of bacteria and leading to calcium carbonate precipitation was proposed as follow [15,16]:

$$Ca^{2+} + Cell \rightarrow Cell - Ca^{2+} \tag{1}$$

$$Cl^{-} + HCO_3^{-} + NH_3 \rightleftarrows NH_4Cl + CO_3^{-} \tag{2}$$

$$Cell - Ca^{2+} + CO_3^{2-} \rightarrow Cell - CaCO_3 \downarrow \tag{3}$$

Along with all these positive attributes of using bacteria in concrete, the disadvantage of use of organic matter on the retardation of setting process of soil-cement mixtures have also been reported by many researchers [17–19]. It has been reported that the presence of organic matter in soil-cement mixtures delay the hydration process of cement, thus affecting the cementing process. Organic compounds with hydroxyl and carboxyl groups may retard the hardening of cement and resulting into no strength gain [18]. During the process of microbial induced carbonate precipitation, different nutrients (both organic and inorganic) are used. The use of these organic nutrients might affect some properties of concrete.

The present study was aimed to test the efficacy of nutrient medium and urea on the structural properties of concrete. The ureolytic bacteria *Bacillus* sp. CT-5 strain isolated from cement sample was used to induce the calcium carbonate precipitation. To evaluate the presence of organic content and nitrogenous material in concrete specimens, carbon and nitrogen content was determined at different depths of the concrete specimens. Furthermore, the concrete specimens were analyzed for compressive strength, sorptivity test, water permeability test, rapid chloride permeability test (RCPT), SEM-EDX and XRD.

2. Materials and methods

2.1. Bacterial strain

Bacillus sp. CT-5 strain isolated from the cement sample was used because of its high urease (UA) producing activity with high efficiency to precipitate $CaCO_3$ crystals [20]. The strain was grown in autoclaved Nutrient broth medium (Peptone 10 g/L, Yeast extract 10 g/L, Sodium chloride 5 g/L). For *in vitro* calcium carbonate precipitation, the culture was grown in Nutrient broth (Himedia, India) supplemented with filter sterilized 2% urea (w/v) (NBU) and 25 mM $CaCl_2$ solution at 37 °C under shaking condition (120 rpm).

2.2. Materials

An ordinary Portland cement (43 Grade) confirming to BIS 8112-2013 [21] was used in the present study. Clean, dry and well graded natural river sand confirming to Zone II was used as fine aggregate (natural river sand). The values of specific gravity and water absorption of fine aggregates was 2.70 and 1.8%, respectively The coarse aggregate used was crushed gravel with nominal particle size of 20 mm and 10 mm. The specific gravity and water absorption of 20 mm aggregates was 2.63 and 1.38% and for 10 mm aggregates, it was 2.65 and 1.4%, respectively. Both fine aggregate and coarse aggregate conformed to BIS: 383-1970 [22].

2.3. Cement paste composition

The change in setting characteristics of cement paste upon addition of bacteria and associated nutrients at the casting stage was investigated by performing initial setting time and final setting time tests on cement pastes. Three types of cement pastes were prepared. One cement paste was made by adding water and termed as control paste mix. Second mix was prepared by mixing cement with 1.3% nutrient broth supplemented with 2% urea (NBU medium) and 25 mM $CaCl_2$. The third cement paste was prepared by mixing bacterial culture grown in NBU medium and 25 mM $CaCl_2$. The consistency of all the mixes was kept same. The composition and nomenclature of the pastes is presented in Table 1.

2.4. Concrete mix proportions

Concrete mix was prepared by using cement: sand: coarse aggregate in the ratio of 1:1.82:3.24 (w/w) and water to cement ratio (w/c) of 0.5. For casting of bacterial treated specimens, nutrient broth with bacterial culture (OD_{600} 0.5) supplemented with 2% urea (w/v) and 25 mM $CaCl_2$ solution (w/v) were used instead of water. The bacterial culture to cement ratio was maintained at 0.5. During casting, the raw material was dry mixed for 2 min in concrete mixer before adding water. After adding water/NBU, the ingredients were mixed for another 2 min. The fresh mix in the plastic stage was immediately transferred to iron moulds. After casting, all specimens were allowed to remain in iron moulds and were kept in casting room at room temperature of 27 ± 2 °C for 24 h. Thereafter, the specimens were demoulded and were cured till the testing age. Four different curing regimes as specified in Table 2 were adopted in this study.

2.5. Test procedures

2.5.1. Compressive strength

Concrete cubes of 150 mm dimension were casted for compressive strength measurements. The effect of incorporating bacterial cells grown in NBU-$CaCl_2$ medium during casting and spraying of bacterial cells suspended in NBU-$CaCl_2$ medium on the mechanical properties of concrete cubes was studied at the age of 7 and 28 days of curing as per BIS 516: 1959 [23] using automatic compression testing machine, COMPTEST 3000. The average of three specimens was taken as the compressive strength of the mix.