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Application of carbonate precipitating bacteria for improving properties and repairing cracks of shotcrete

Hamid Kalhori, Raheb Bagherpour *

Department of Mining Engineering, Isfahan University of Technology, Isfahan 8415683111, Iran

HIGHLIGHTS

- Calcite producing bacteria improved the strength properties of shotcrete.
- Influence of bacteria on shotcrete were more noticeable in comparison with concrete.
- Use of bacteria leads to reduction in permeability and water absorption.
- Shotcrete crack healing was observed in bacteria-exposed shotcrete specimens.
- SEM and XRD analysis indicated the formation of calcite in bacterial shotcrete.

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ABSTRACT

Shotcreting is a construction technique commonly used in many civil and mining engineering applications. Cracking is an unavoidable and inherent weakness of most cement-based construction materials including shotcrete. In this study, the effect of *Bacillus Subtilis* on healing and mechanical properties of shotcrete was evaluated. For this purpose, bacteria were introduced into mix design and curing solution in order to examine the effect of each approach on the compressive strength, tensile strength, permeability, porosity and healing of shotcrete specimens. The results of uniaxial compressive test showed up to 30% increase in the compressive strength of bacteria-exposed shotcrete specimens compared to control specimens. This strength improvement was 10% more in shotcrete specimens than in the conventional cast concrete specimens with the same mix design. The presence of bacteria, both in the mix design and curing solution, was found to enhance the tensile strength and decrease the water absorption and porosity of shotcrete. The maximum reduction in water permeability at 28 days was observed in the specimens cured in the bacteria-containing solution. The ability of bacteria to heal the cracks created in the specimens was also evaluated in the present work. Bacterial precipitation of calcium carbonate in the pores of specimens was confirmed by SEM/XRD analysis. The results give clear evidence supporting the utility of calcium carbonate precipitating bacteria for healing the cracks and improving the durability of shotcrete.

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1. Introduction

By definition, sprayed concrete or shotcrete is a concrete or mortar mixture that is pneumatically projected on a surface at a high velocity. Shotcrete is known as a material of high strength, suitable durability, and workability. Spraying the concrete on a surface involves the use of compressed air, thus there is no escape from the emergence of numerous tiny air voids in the resulting shotcrete. Because of these air voids, properties of shotcrete differ significantly from those of conventional cast concrete [1]. Nowadays, shotcrete plays an essential role in civil and mining constructions [2–7]. In hard rock tunneling, shotcreting is an important and common technique for stabilization and securing of the rock. The widespread use of shotcrete as a stabilizer highlights the importance of its performance and reliability and its ability to maintain its function with minimum need for inspection and repairing operations, which may cause problematic traffic interruptions [8]. The main cause of cracking in shotcrete is the bending moments in the shell induced by heterogeneous soil and rock conditions. However, the shrinkage and thermal gradients may also cause tensile loads leading to nucleation and propagation of cracks in shotcrete matrix [9]. Experiences from tunneling projects have shown that extensive cracks in shotcrete can occur, which significantly reduces

* Corresponding author.
E-mail address: bagherpour@cc.iut.ac.ir (R. Bagherpour).

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the performance and lifetime of support system if instant repairs are not made. The repair of cracks is a complex process since it requires considering many factors and expensive repairing tasks [10]. In recent years, promising repair methods for eco-friendly restoration of concrete are being investigated and developed in several laboratories. One such a method involves the use of mineral-producing bacteria [11]. The engineering use of bacteria for environmental purposes is a rapidly developing field [12–14]. Substantial research on carbonate precipitation by bacteria has been carried out using ureolytic bacteria. These bacteria produce an enzyme called urease that catalyzes the hydrolysis of urea to ammonia and carbonate. When this hydrolysis occurs in a calcium-rich medium, calcium carbonate precipitates from solution in the form of a solid crystalline material [15,16]. Initial advances in the use of bacteria for biological calcite deposition was made in geotechnical engineering, where they were used for strengthening and improvement of soil mechanical properties [17,18]. Over the past few years, however, considerable studies have also been reported on the use of calcite producing bacteria for repair of concrete cracks [19–21], compressive strength improvement of concrete [22,23], consolidation of concrete surfaces [24,25] and several other areas. Ghosh et al. [26] studied the use of a thermophilic, anaerobic microorganism belonging to the *Shewanella* species for improving the strength of cement-sand mortar. They observed the maximum 28-day compressive strength in specimens containing 10^5 cells/ml of bacteria (25% increase relative to control). The SEM micrographs obtained in this study confirmed the microorganism-induced growth of fibrous filler materials within the pores. De Muynck et al. [27] used the *Bacillus Sphaericus* for creating a calcium carbonate surface treatment and investigated the changes in water absorption and gas permeability of the resulting specimens. The results indicated the bio-deposition of a calcium carbonate layer on the surface of mortar specimens leading to a decrease in the permeation properties. They reported the high performance along with some other traditional surface treatment methods. Reddy et al. [28] investigated the effect of different concentrations of *Bacillus Subtilis* on compressive strength of a number of cement specimens. Experiments indicated that the addition of bacteria with a cell concentration of 10^5 cells/ml increases the compressive strength of standard grade concrete up to 15% at 28 days as compared to conventional concrete. Moreover, they reported that bacteria-containing specimens showed significantly better split tensile strength and acid resistance than the control specimens. Achal et al. [29] used *Bacillus sp.* CT-5 for making a self-healing cement mortar and showed a maximum of 40% increase in the compressive strength of microbial remediation specimens. These researchers emphasized the utility of bacteria for achieving improved durability and self-healing ability of cracks in building structures. Luo et al. [30] studied some of the factors influencing the healing capacity of bacteria-based self-healing concrete. These researchers created cracks with different dimensions in the specimens and investigated the effect of crack width, curing procedure, and cracking age on the self-healing property. They reported that as the average crack width increases self-healing becomes more difficult, and microbial repair agent shows significantly limited healing ability for cracks wider than 0.8 mm. Elsewhere, water curing was reported to lead to the best self-healing capability. Also, the crack-healing ratio of specimens decreased significantly along with the extension of cracking age. Khaliq and Ehsan [31] compared different methods of introducing bacteria to concrete and investigated their effect on healing ability. In this study, *Bacillus Subtilis* was introduced to concrete specimens both directly and by various carrier compounds such as lightweight aggregate and graphite nano platelets. Measuring the crack healing efficiency in the resulting pre-cracked specimens with various curing ages showed that graphite nano platelets are suitable for healing at an early age while lightweight aggregates are more suitable for later days.

Although several research works have used bacteria for improving concrete properties, no such studies have been reported on the use of bacteria in shotcrete. Considering the above efforts and successes in the use of different bacteria for improving the strength and durability of concrete and the widespread use of shotcrete in construction and mining activities, this study investigates the effect of calcium carbonate precipitating bacteria on self-healing capability and mechanical properties of shotcrete. In the present work, bacterial self-healing capability was achieved by introduction of a microbial healing agent to either the mix design water or curing environment of shotcrete. The effect of both approaches on healing properties, compressive strength, tensile strength, water absorption, and permeability of the resulting shotcrete was also investigated.

2. Materials and methods

2.1. Microorganism and growth condition

In order to use them as a healing agent in concrete, bacteria should be able to produce huge quantities of calcium carbonate in the alkaline environment of concrete and withstand high pressure and alkaline atmosphere in concrete. For this purpose, a Bacillus species called *Bacillus subtilis* PTCC 1254 (NCIM 2479, NCIB 8646, ATCC 12711) was used in the present study. *Bacillus subtilis* is a gram-positive bacterium with high spore formation capability that can survive harsh environments. Bacterial spores are specialized cells that can endure high mechanical and chemical stresses and alkaline environment, making it an ideal selection for using in shotcrete mixture. According to supplier's recommendation, bacteria were cultured in liquid Nutrient Agar containing 5.0 g peptone and 3.0 g meat extract per liter of distilled water. Next, 0.01 g $MnSO4{\cdot}H2O$ was added to the culture medium to enhance sporulation and pH was adjusted to 7. Liquid medium was sterilized by autoclaving for 20 min at 121 °C. After inoculation under laminar flow hood, the culture was incubated at 35 °C in a shaker incubator at 130 rpm for 24 h.

The bacterial cell concentration was measured by serial dilution technique, and cell concentration curve and equation was obtained by measuring the optical density. For this aim, after 24 h of incubation, a certain quantity of culture was extracted and its bacterial cells were isolated and washed by centrifugation (at 5000 rpm, 10 min, 4 °C). The isolated cells were diluted to the specific volume using distilled water and then were serially diluted. Diluted solutions were inoculated on a solid medium (liquid medium plus 1.5% agar) and colonies of bacterial cells were counted. Meanwhile, the absorbance (optical density) of the corresponding solutions was measured at 600 nm wavelength using a spectrophotometer, and curve and equation of bacterial cell concentration were obtained. It is notable that the spore concentration in samples was kept equal to 2.2×10^6 cells/cm^3 of shotcrete mixture.

2.2. Mix proportions

All specimens were prepared using the ordinary Portland cement (CEM I-32.5). The chemical properties of the cement used in the specimens are given in Table 1. Locally available well-graded washed river sand with fineness modulus of 2.90 and specific gravity of 2.65 (particle size of 0–4.75 mm) was used as fine aggregate and crushed stone with a specific gravity of 2.70 (particle size of 4.75–10 mm) was used as coarse aggregate. The mix proportion of shotcrete was designed according to ACI 506R-05 [32] to have the 28-day compressive strength of 28 MPa. The resulting

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