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Influence of bacteria on compressive strength and permeation properties of concrete made with cement baghouse filter dust

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HIGHLIGHTS

- Paper presents properties of bacterial concrete containing CBFD.
- Calcite producing bacteria improved the strength properties.
- Porosity and permeability increased with CBFD but reduced with bacteria.
- SEM and XRD analysis indicated the formation of calcite in bacterial concrete.

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ABSTRACT

The present study investigated the influence of cement baghouse filter dust (CBFD) in control and bacterial concrete, as partial replacement of ordinary Portland cement (0%, 10%, 20% and 30%) on compressive strength, water absorption, porosity, chloride permeability and sorptivity at 28 and 56 days of curing. Calcite producing bacterial strain AKKR5 was mixed in water during concrete mixing with the cell concentration of 10^5 cells/mL. X-ray diffraction analysis confirmed the calcite production by bacterial strain. Control and bacterial concrete with 0% CBFD achieved best results for compressive strength of 32.89 and 34.66 N/mm^2, respectively, but with increasing the percentage of CBPD the compressive strength was decreased. Water absorption was significantly reduced in bacterial concrete compared to control concrete. The chloride permeability of concrete specimens containing control and bacterial CBFD concrete showed “moderate” to “low” permeability except 30% CBFD concrete with increasing curing period from 28 to 56 days. SEM and XRD results exhibited formation of ettringite in pores, increased calcium silicate hydrate (CSH) and calcite production which densified the concrete structure, and thus, increased the compressive strength in bacterial concrete containing CBFD. It was also found that CBFD is not cementitious in nature and replacing it with cement will reduce cement content. At 28 days, concrete mixture containing 10% CBFD exhibited compressive strength equivalent to target strength of 28 N/mm^2 required for designed control mix.

1. Introduction

Concrete is a combined building material, consists of cement, coarse and fine aggregate. Cement plays an important role in the production of mortar and concrete due to its binding properties, and thus acts as a major constructional material of choice in building and structures. Rapid industrialization and urbanization increases the demand of building and construction material for infrastructure development, thereby, continuously driving the cement industry to keep growing. The increasing cement generation is also associated with certain challenges such as energy and resource conservation, cost of production, green house gas emissions, etc. It is estimated that production of Portland cement clinker alone contributes 7% global CO_2 emissions, therefore, concrete does not appear to be a sustainable material [1].

Supplementary cementitious materials (SCMs) are recognized worldwide as potential cement replacement materials frequently

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used in concrete mixes to decrease cement contents, improve workability, increase strength and improve durability. Majority of the industrial by-products such as fly ash, silica fume, blast furnace slag, cement by-pass dust, etc. are used as SCMs. Every year large quantities of industrial by-products are produced by various industries. Utilization of these by-products in cement/concrete not only stops them from being land-filled but also enhances the properties of concrete in the fresh and hardened states. In addition, the usage of SCMs conserves energy and has environmental benefits because of reduction in carbon dioxide release as a consequence of reduction in manufacture of Portland cement.

During the production of Portland cement (PC) a number of air pollution control (APC) devices are used to limit emission of gases and capture particulate matter (PM). The captured particulate matter from Baghouses as well as other APC devices is referred as cement baghouse filter dust (CBFD). CBFD is a finely powdered partially calcined by-product, and is distinguished from cement kiln dust (CKD) on the basis of lower content of alkali salts and metal content [2]. The composition of cement dust is quite variable from source to source due to variation in amount of fine calcined and uncalcined feed materials, fine cement clinker, and fuel combustion by-products [3]. The elemental composition of baghouse filter dust falls within the ranges of the composition of CKD. Hayes et al. [2] analyzed the composition of baghouse filter dust and reported calcium carbonate as the major crystalline phase followed by other mineral forms in minor (<10% wt.) and trace (<1% wt.) constituents.

Concrete requires different degrees of durability depending on the exposure environment and properties desired. Durability is described as the competence of concrete to oppose chemical attack, weathering action, and abrasion while preserving its much needed engineering properties such as compressive strength, modulus of elasticity, creep, shrinkage, etc. Concrete remains durable under conditions of strong and inert graded aggregate, ingredients in the mix with minimum impurities such as alkalies, chlorides, sulfates and silt, dense structure and low permeability. Cracking in concrete is another phenomenon that affects the concrete's structure integrity and durability. These durability related problems poses a negative impact on the national economies that is reflected by the financial budget spent on the repairing and maintenance of the concrete structures. Jonkers et al. [1] reported that in United States around 4 billion dollars are spent annually on the repairing and maintenance of concrete highway bridges due to reinforcement corrosion. Conventionally, a variety of sealing agents such as latex emulsions are there that seals the pores and cracks and thus reduces the permeability of the structure but they suffer from serious limitations of incompatible interfaces, susceptibility to ultraviolet radiations, unstable molecular structure and high cost.

A biologically induced precipitation in which an organism creates a local micro-environment with conditions allowing optimal extracellular chemical precipitation of mineral phases, called biomineralization [4], has been studied by several researchers in mortar [4–6] and concrete [7–9]. Microorganisms are microscopic, minute living organisms which are very small to be seen with the naked eye. There are numerous diverse microbial species that contribute in the precipitation of mineral carbonates in numerous natural environments include soils, geological formations, freshwater biofilms, oceans and saline lakes. While the precise role of the microbes in the carbonate precipitation process is still not clear but most of the bacteria are capable of calcium carbonate precipitation [10] and precipitation occurs as a by-product of common metabolic processes such as photosynthesis, sulfate reduction and urea hydrolysis [11]. The hydrolysis of urea generates carbonate ions which upon hydrolysis in calcium rich environment, produces calcite. The rate of carbonate formation has an important role to play in the strength of precipitated crystals and under suitable conditions it is possible to control the reaction to generate hard binding bio-cement.

Bacterial calcium carbonate precipitation results from passive carbonate nucleation that occurs from metabolically driven changes in the bulk fluid environment surrounding the bacterial cells. This increases the mineral saturation and induces nucleation [12]. In the ureolysis driven system, this occurs from an increase in pH due to ammonification [13]. Active carbonate nucleation occurs when the bacterial cell surface is utilized as the nucleation site. The cell clusters exhibit a net electronegative charge which favors the adsorption of Ca^{2+} ions. The Ca^{2+} ions attract CO_3^{2-} and HCO^{3-} ions, which will eventually form calcium carbonate precipitates [11,14].

One of the primary applications of biomineralization is the plugging of porous media with applications leaning toward bioremediation [14] and involves many different factors, such as soil alkalinity, temperature, and pressure. Members of the genus *Bacillus* are Gram-positive, rod-shaped, endosporeforming bacteria commonly found in soil [15]. *Bacillus pasteurii*, a member of this genus, converts urea to ammonium carbonate more actively than any other known bacterium. Therefore, *B. pasteurii* and other members of the *Bacillus* genus are incorporated into studies to determine their influence on calcium carbonate precipitation in various environments. Ferris et al. [16] reported that the hydrolysis of urea by *B. pasteurii* (now reclassified as *Sporosarcina pasteurii*) is temperature dependent and that the highest calcite precipitation rates occurred near the point of critical saturation [14]. Experiments performed by Stocks et al. [13] indicated that urease activity at high pH in *B. pasteurii* favoured calcium carbonate precipitation.

Several research groups have investigated the possibility of bio-mineralization as an effective method to remediate cracks and fissures in concrete structures. Cracks filled with a mixture of *B. pasteurii* and sand showed a significant increase in compressive strength and stiffness, compared to cracks without cells [17]. Rodrigues et al. [18] studied the effectiveness of *Myxococcus xanthus* in precipitating calcium carbonate and indicated that it can be used in the conservation of ornamental limestone statues or carvings, similar to its use in concrete remediation.

Chahal et al. [7] presented the effect of the ureolytic bacteria (S. pasteurii) on the compressive strength of concrete containing 5% and 10% of silica fume as partial replacement material to cement. Test results indicated that inclusion of S. pasteurii enhanced the compressive strength to 38.2 N/mm^2 and 44 N/mm^2 at 28 and 91 days. Inclusion of cement by-pass dust also enhanced the strength and durability of concrete. Dhir et al. [19] observed that replacement of up to 10% cement by cement by-pass dust does not seem to have any significant adverse effect on strength especially at low w/c ratios. Addition of 10^5 cells/ml of bacteria with 10% fly ash content in concrete exhibited minimum water absorption (3.25%) values [7]. Achal et al. [20] concluded that addition of bacteria *S. pasteurii* (Bp M-3) in concrete showed "low" (1000–2000 C) chloride permeability whereas control concrete specimens showed "moderate" chloride permeability. The average charge passed was 3177 C for the control samples treated with bacteria, whereas for samples prepared with bacterial cells in nutrient broth and corn steep liquor media it was 1019 and 1185 C, respectively. Application of bacteria on top of concrete also helps in lowering the permeation properties making the concrete more durable [9,21].

Several studies have been reported on the use of CKD as partial replacement to cement in the production of mortar [22] and concrete [23–25] but quite a few research works has been published by using CBFD in concrete as supplementary cementitious material replacing cement partially. Literature on the use of bacteria in concrete containing CBFD as partial replacement is not extensive; therefore, the present study was conducted to provide technical