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Influence of molding process on mechanical properties of sandstone cemented by microbe cement

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ABSTRACT

A new generation of cement, microbe cement has been developed due to the ever increasing awareness of environmental protection. Microbe cement is a new strengthening technique based on microbiologically induced precipitation of calcium carbonate. This paper confirms the feasibility of microbe cement binding loose sand particles and presents results from a laboratory research on the influence of molding process (non-pressure molding, pressure molding, discontinuous non-pressure molding and pumping molding) on the mechanical properties of sandstone microbe cement bound. The results showed that the ways of molding procedure had a strong influence on the mechanical properties of bio-sandstone. The strength, which was up to 12.0 MPa, of sandstone microbe cement bound by adopting pumping molding process was higher than other three processes. Meanwhile, Scanning electron microscope (SEM) image analysis technique was adopted to measure the corresponding variation of porous characteristics caused by different molding processes. The results indicate that the microstructure of bio-sandstone adopted by pumping molding has lower porosity and higher content of precipitated calcium carbonate than other three molding processes.

1. Introduction

The cement industry has for some time been seeking procedures that would effectively reduce the high energy and environmental costs of cement manufacture. One such procedure is the use of alternative materials as replacements for cementation loose particles. In recent years, microbe cement, which only consists of three materials: alkalophilic microbe, substrate solution and calcium ion solution, has experienced an increased level of interest. This type of process is more environmentally friendly than conventional treatment methods and often found in naturally cemented deposits. The method relies on the bacterially induced formation of a compatible carbonate precipitation around individual particles and at particle–particle contacts.

The great promise of the use of microbe cement treatment has been demonstrated in a variety of fields. Several researchers have shown that microbe cement can be used to improve the mechanical properties (cohesion, friction, stiffness, strength) and permeability of porous materials [1–7]. Moreover, microbe cement has been investigated for its potential to enforce or repair construction materials such as limestone and cementitious [8–12]. A series of applications aimed at modifying the properties of soil and sand, i.e. for the enhancement of oil recovery from oil reservoirs [13–15] and another series of applications were situated in the field of bioremediation [16–20].

In this paper, firstly, the cementation mechanism of microbe cement is illustrated in detail. Secondly, the production of sandstone, which microbe cement bound, using four different molding processes, i.e. non-pressure molding, pressure molding, discontinuous non-pressure molding and pumping molding, has been investigated. Finally, the microstructure analyses of sandstone microbe cement bound investigated by SEM image analysis is presented. The results of these studies demonstrate the feasibility of developing more environmentally friendly microbe cement and show that the ways of molding procedure have a strong influence on the mechanical properties of bio-sandstone.

2. Cementation mechanism of microbe cement

Microbe cement has been proposed as a novel method for cementing loose sands in civil structure. This process of cementation has a complex mechanism. Firstly, the substrate solution is broken down into carbon dioxide by the bacteria-producing urease according to the reaction [21–23].

$$\text{Substrate B} + 3H_2O \xrightarrow{\text{Bacteria A}} CO_3^{2-} \quad (1)$$

Secondly, the value of pH around surrounding environment is increased through the breakdown of substrate. At the meantime, in the presence of calcium ions, the followings are triggered [3,23,24]:

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$$Ca^{2+} + HCO_3^- + OH^- \rightarrow CaCO_3 \downarrow + H_2O \quad (2)$$

$$Ca^{2+} + 2HCO_3^- \Longleftrightarrow CaCO_3 \downarrow + CO_2 + H_2O \quad (3)$$

These chemical ions diffuse through the cell wall of the microbe and into the surrounding solution. Two reactions spontaneously occur in the presence of water; ammonia is converted to ammonium and carbon dioxide equilibrates in a pH-dependent manner with carbonic acid, carbonate and bicarbonate ions. The net increase in pH is due to hydroxyl ions generated from the production of NH_4^+ which exceeds the available Ca^{2+} for calcite precipitation.

In addition to calcite precipitation from the above mechanism, calcium ions deposit on the surface of microorganisms with a net cell surface charge that is negative. The equations for the precipitation of calcite at the cell surface serving as the nucleation site are as follows [3,25]:

$$Ca^{2+} + Cell \rightarrow Cell - Ca^{2+} \quad (4)$$

$$Cell - Ca^{2+} + CO_3^{2-} \rightarrow Cell - CaCO_3 \downarrow \quad (5)$$

De Muynck et al. [8] have explained vividly. Firstly, calcium ions in the solution are attracted to the bacterial cell wall due to the negative charge of the latter and upon addition of substrate to the bacteria. Secondly, in the presence of calcium ions, this can result in a local supersaturation and hence heterogeneous precipitation of calcium carbonate on the bacterial cell wall. After a while, the whole cell becomes encapsulated, limiting nutrient transfer, resulting in cell death. Finally, the formation of calcite crystals by bio-mediated at the particle–particle serves as coat or bridge function so that the loose sands become entirety. The microbe cement could play a part cementation function by above procedures. The state before and after cementing loose sands is given in Fig. 1. When the incompact sands are put into the injector, there are lots of interspaces between the sands as shown in Fig. 2a. The bacteria solution should be firstly introduced into the sand and after the solution is fully exudative, numerous thalli will remain on the surface of sand as Fig. 2b shows. Then the mixture of substrate and calcium ion solution shall be injected, and the cementation substance will be produced from bio-mineralization. The cementation substance will attach to the sand surface, and will enwrap the bacteria with the increasing of its content as in Fig. 2c. From this circulation, the new born $CaCO_3$ will cover the old one, until the adjacent sand grains are connected to form a whole sand body with a certain degree of strength as in Fig. 2d [26]. The microstructures of bio-sandstone are shown in Fig. 3. The results show that calcium carbonate crystals (light gray) have precipitated between the sand grains (dark gray) induced by microbial catalyzed hydrolysis of substrate. In addition, the bio-sandstone remains porous (black).

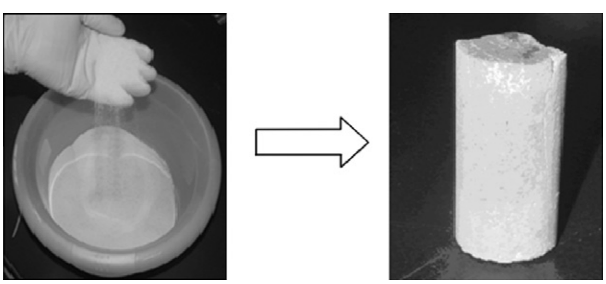

Fig. 1. Loose sand to sandstone cemented by microbe-based cement.

3. Experiments and methods

3.1. Materials

3.1.1. Microbe cement

Microbe cement only consists of three materials: alkalophilic microbe, substrate solution and calcium ion solution. Microbe having OD_{600} value of 1.68 and enzyme urease activity value of 4.4 mM/min was used in this study. Cultivation of the organism was conducted in a medium containing 3 g/l yeast extract and 5 g/l peptone. In general, the harvest microorganism was stored at 4 °C prior to use. The concentration of substrate solution and calcium ion solution was 1–3 M/L, respectively.

3.1.2. Aggregate

The aggregate used in this study was less than 300 μm of quartz sand (grain size characteristics: d_{10} = 150 μm (10% of the grains was lower than a diameter of this size); d_{90} = 300 μm).

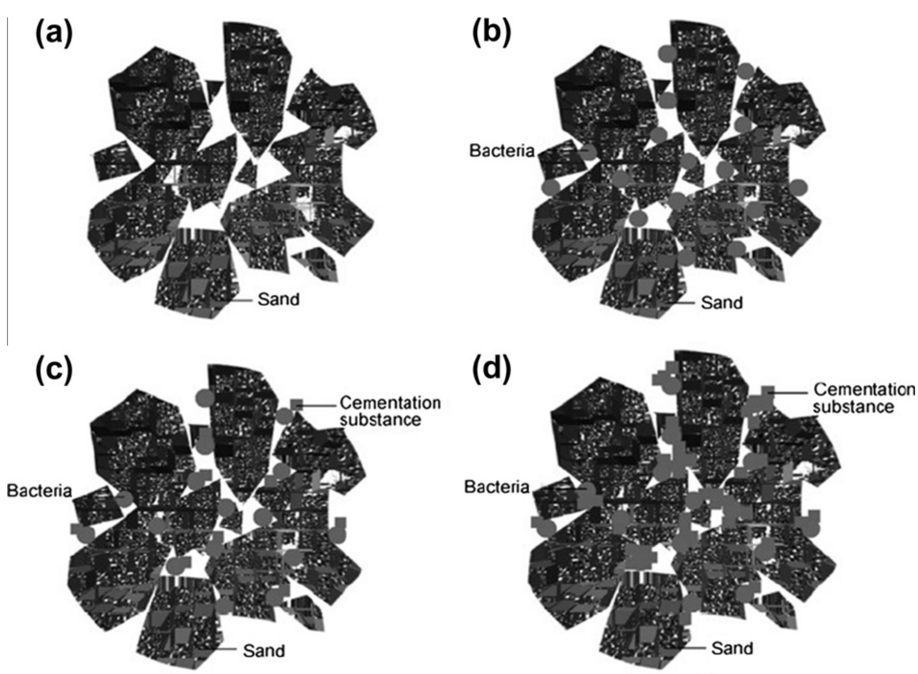

Fig. 2. Cementation mechanism of microbe-based cement.