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Bio-bricks: Biologically cemented sandstone bricks

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HIGHLIGHTS

- A novel technique to manufacture bio-bricks using a biologically mediated natural cementation process is presented.
- Results show that bio-bricks can have compressive strengths up to 2 MPa.
- P-wave velocity measurements show bio-brick stiffness to be relatively uniform and high.
- Bio-bricks are comparable to bricks prepared with the more conventional cement and hydraulic lime additives.

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ABSTRACT

The cementation of sand into sandstone through microbial activity is a novel technology with a wide range of possible applications. The cementation process involves the introduction of bacteria and nutrients to sand, and through bacterial processes calcite precipitation binds particles together, ultimately creating a sandstone material. This technology could provide a new, more sustainable building material in the form of "bio-bricks". This paper describes the treatment technique as well as results from testing after brick manufacturing. Bricks were tested to determine compression (p-wave) wave velocity, unconfined compression strength, and calcite concentration. P-wave velocity, stiffness, strength, and calcite content of bio-bricks all increase with further treatment of bacteria and cementation media. Results show that bio-bricks can have strengths ranging from 1 MPa to 2 MPa. Bio-bricks are comparable in terms of stress and stiffness to bricks prepared with the more conventional cement and hydraulic lime additives.

1. Introduction

The global use of resources and emphasis on sustainable infrastructure is a growing societal issue civil engineers must address [21]. The international population is growing at an unprecedented rate, and in response, civil infrastructure must expand and be rehabilitated in a sustainable manner. The demand on natural resources is far greater than the supply in both developed and developing countries [1]. Sustainable development must consider the energy and material flows through the construction, maintenance, dismantling, and material disposal related to a project [28]. Meeting the societal demands with locally available resources and minimal material and energy promote a sustainable approach to development.

Biological processes have been harnessed for a multitude of engineering applications [9,10], DeJong et al. [11]. Bio-geochemical processes that induce mineral precipitation have been utilized for many applications, including improving the strength and stiffness of soil [8,32,20] as an alternative to traditional chemical grouting which can be environmentally hazardous [17]. Microbially induced calcite precipitation (MICP) can be used for a variety of other applications including environmental remediation [13], improved durability and remediation of concrete [25,7], calcium removal in wastewater [15], and carbon sequestration [26].

Although various forms of MICP are available using different bacterial and precursors, the form of MICP treatment used for this research utilized natural soil bacteria to metabolize urea, increasing the pH of the pore water, promoting mineral precipitation. Ureolytic bacteria are prevalent in natural soils; they increase the alkalinity of the soil by hydrolyzing the urea to produce ammonia and carbon dioxide. This induces calcite precipitation primarily at particle–particle contacts, which increases the strength and stiffness of the sand. The amount of calcite cementation is proportional to the concentrations of chemicals supplied (e.g. urea and calcium) and the number of treatments performed. The reaction network for the net urea hydrolysis reaction and formation of calcite is:

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$$NH_2 - CO - NH_2 + 3H_2O \rightarrow 2NH_4^+ + HCO_3^- + OH^-$$

$$Ca^{2+} + HCO_3^- + OH^- \rightarrow CaCO_3 + H_2O$$

Current methods for brick manufacturing vary widely, but most methods include high energy processes of compression under high stresses and/or baking at high temperatures. The most common method of brick manufacturing is by firing clay at high temperatures. Red clay bricks are typically placed in wood molds and dried in the sun for 2–3 days and then baked in the oven for 24 h at temperatures up to 1200 °C [6]. Engineering properties and physical characteristics differ between red clay bricks primarily due to the clay source and firing temperature. For example, Lower Oxford Clay based bricks have a 28 day unfired strength of 3.5 MPa and a fired strength above 20 MPa [22] (and other references in Table 1). Alternatives to red clay bricks include sand–lime bricks, which are manufactured using water, sand, and lime mixed together, compacted together at a pressure of 20 MPa and then autoclaved for up to 9 h at temperatures of up to 190 °C (Fang et al. [12]). Another method uses clay in addition to lime, cement, and a manufacturing byproduct such as ground granulated blast furnace slag. The bricks are cured at room temperature, yielding strengths between 2.7 and 5 MPa [23]. Other methods of manufacturing earth-based building materials consists of adobe, cob, rammed earth, and compressed earth bricks [29,24]. The range of strengths and modulii for these and other bricks are summarized in Table 1.

This paper summarizes a research program undertaken to develop a natural, bio-mediated process for the manufacturing of bio-bricks (Bernardi [4]). The materials, treatment methods, and measurement techniques are presented first. Bricks produced using the novel technique are compared against cement and lime treated bricks. Results assessing the treatment uniformity within individual bricks, as measured and indicated by shear and compression wave velocity, are presented. The correlation between cementation level (precipitated calcite concentration) and wave velocities is then investigated. A comparison of brick strength between the three brick types is presented, followed by correlations between compressive strength and velocity measurements.

2. Materials and test methods

2.1. Soil

The sand used for production of all bricks was silica rich #1 masonry sand, quarried in Chico, California. This sand was used because it is moderately graded, locally produced, and available in large quantities. Salient sand characteristics are presented in Table 2.

2.2. Bacteria and growth conditions

The soil bacterium utilized in this study was *Sporosarcina paseurii* (ATCC 11859). Cultures were grown in an Ammonium-Yeast Extract media (ATCC 1376) as described in Mortensen and DeJong [20] (0.13 M Tris Buffer, 10 g of $(NH_4)_2SO_4$, and 20 g of yeast extract per liter of deionized water). The bacteria were inoculated in the growth media and incubated aerobically in a 30 °C water bath shaken at 200 rpm for approximately 24 h. Bacteria were incubated until samples obtained an optical density near 1.0 using a spectrophotometer (600 nm wavelength). The sand was inoculated with the bacteria by percolating the bacterial solution through the sand top-down, which was retained for 4 h in the soil before treatments with cementation media began.

Table 1
Strength of other bricks and materials.

Bricks	Strength (Mpa)	Elastic modulus (MPa)
Autoclaved bricks	20	–
Red clay bricks	>20	–
Compressed earth block	0.7–3.1	200
Rammed earth	0.75–1.5	72–102
Adobe	1.2–1.8	100–300
Sandstone	70	45,000
Limestone	10–70	–

[12,14,5,18,30,3,27,16].

Table 2
Sand characteristics.

Material	D_{50} (mm)	C_u	C_c	G_s	e_{min}	e_{max}	Mineralogy
#1 Masonry sand	0.42	2.6	1.2	2.6	0.5	0.8	Quartz

2.3. Cementation media

A urea-calcium medium was used to drive calcite precipitation. The cementation media consisted of urea (200 mM), calcium chloride (100 mM), and nutrient broth (0.5 g/L). The nutrient broth, which contains beef extract and peptone, was used to enable bacteria reproduction within the brick mold.

2.4. Brick mold

Three identical brick molds were fabricated from PVC plastic, with each mold containing five bricks with dimensions of 91 mm by 58 mm by 200 mm (similar dimensions as standard red clay bricks, Fig. 1, Bernardi [4]). The mold is assembled with screws and silicone sealant with drain holes at the mold base to enable fluid to percolate through. The mold base enables saturation of the mold during bacterial treatment and relatively unobstructed flow during cementation treatment. Three plastic screens with different opening sizes (3.360 mm, 0.711 mm, and 0.178 mm) were placed at the mold base to prevent soil loss during treatment. The sand is then placed, three additional screens were placed on top of the sand, and a low confining stress (~10 kPa) applied with a rubber band. Coarse gravel is placed on top to prevent erosion of the sand when the treatment solution is added.

2.5. Preparation and treatment programs

2.5.1. MICP treatment method

The bacterial solution was added to the sand by percolation (i.e. unrestrained flushing of fluid from top to bottom). The treatment method implemented was selected in order to ensure bacteria attachment at particle contacts within the permeable sand matrix. Effluent consisting of the bacterial solution was cycled through the sand two additional times to improve bacteria attachment throughout the sample, and during the second cycle the mold was sealed to create fully saturated conditions. Treatment media was added to the sand by percolation. Three brick molds were treated for different amounts of time. Since the bio-bricks were going to be compared to lime and cement treated bricks that were cured for up to 28 days, an equivalent treatment time was devised. Treatments ranged from 1 to 5 times per day, depending on permeability reduction from the treatment, so an average of 3 treatments per day was defined as equivalent to one day of curing of conventional bricks. The molds were treated at 7 days (21 treatments), 14 days (42 treatments), and 28 days (84 treatments). A 12 h retention was usually allowed overnight before treatment started the following day. All treatments contained the cementation media (Table 2). pH readings were made of the influent solution and the immediate effluent of each brick with the use of pH strips (displaying pH in the range of 6.5–9.0). Occasionally excess calcite precipitation on the injection face of the bricks reduced permeability sufficiently that the mold was partially disassembled and the screens cleaned. Once the required treatments were completed, two pore volumes of deionised water with 50 mM sodium chloride were percolated through to rinse excess chemicals from the pore space. The mold was then disassembled and the bricks were oven dried overnight in a 77 °C oven. The brick dimensions were measured and the mold was weighed again to estimate changes in dry density and void ratio.

2.5.2. Lime treatment method

Lime bricks were prepared by combining dry sand with varied volumes of hydraulic lime. The evaluated percents of hydraulic lime to sand by volume were 20%, 25%, 30%, 40%, and 50% for each set of five bricks (these correspond to percentages by weight of about 10.1%, 12.7%, 15%, 20.9%, and 26.7%). These mixtures bracket the strengths that were expected from the bio-bricks (~2 MPa) and were selected in part from manufacturer recommendations. The lime used was from the manufacturer St. Austier and is a natural hydraulic lime (NHL5) with approximately 20–30% clay included as the silica source. The lime and the sand were measured, dry mixed, and then water was added until proper workability was achieved (~250 mL of water per brick). The sand–lime mixture was placed in approximately 2.54 cm lifts and tamped 50 times using the steel overburden stress tamper. The overburden stress was then applied the same way as the bio-brick treatment. The three brick molds were used to make batches of bricks to be tested at different curing times. The bricks set for 2 days and then cured for 7, 14, and 28 days in a constant humidity chamber (~95% humidity, ~13.3 °C). After curing was complete, the brick molds were disassembled and bricks dried for up to 2 days in a 77 °C oven before testing.