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On possibility of improvement of compacted silty soils using biodeposition method

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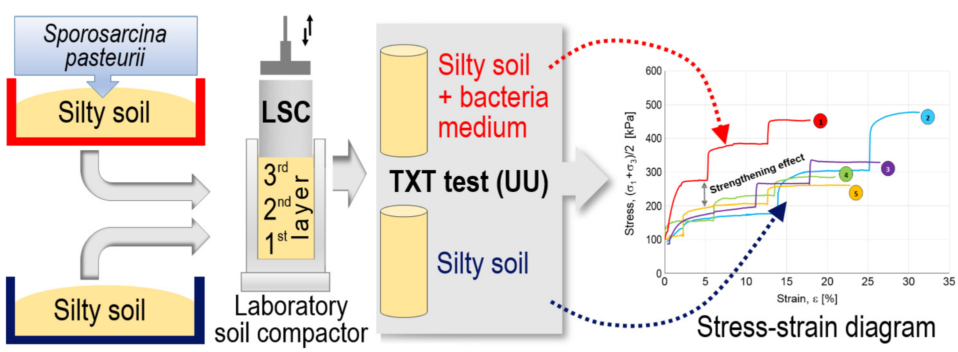
HIGHLIGHTS

- *Sporosarcina pasteurii* strain ensures lithification and increase of soil rigidity.
- Biodeposition highly improves shear strength of silty soil at small deformations.
- *Sporosarcina pasteurii* strain is resistant to dynamic impact typical for earthworks.
- Observed strengthening effect may be applicable in building earth structures.

GRAPHICAL ABSTRACT



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ABSTRACT

Contemporary challenges and results of the research to date show that the search for environmentally-friendly ways of soil improvement is the right direction. The paper presents biogrouting of silty soil compacted using standard energies in the laboratory soil compactor. An improvement of transition soils by biodeposition using *Sporosarcina pasteurii* has been undertaken. Biodeposition has increased shear strength in the triaxial compression test. It has been concluded that application of bacteria solution on the soil ensures lithification and a significant increase of soil rigidity. Resistance of *Sporosarcina pasteurii* strain to dynamic impact during soil compaction allows a possible application of these microorganisms in geoengineering.

1. Introduction

Intensified development of urban areas and requirements for subsoils of contemporary engineering structures make soil improvement one of the most common techniques used in geotechnical engineering nowadays. Standards of contemporary construction frequently impose a requirement of using near-surface or deep soil improvement until the appropriate bearing capacity is achieved. Another example illustrating this phenomenon may be the categorisation of soils and rules of their use for road construction (in Poland, they are categorised in the Regulation of the Minister for Transport and Maritime Economy – Journal of Laws no. 43 of 14-05-1999). Limited load-bearing capacity of soil may be affected both by its physical properties (moisture, porosity, grain size distribution), and mineralogical characteristics. Hence, key measures undertaken with the view to improve the construction quality of soil are grain size improvement, compaction, drying, or improvement by grouting. The extent of appli-

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cability of different methods strictly depends on the soil's conditions and geological properties. A special group of soils with adverse geotechnical properties, usually with lower bearing capacity and high heaving frost potential, are soils containing a large share of dust fraction, such as sandy silts or silty sands [1,2].

As fitness of soil for construction purposes can be analysed in two aspects – as a construction material or subsoil for engineering structures – the techniques for soil improvement vary. Cement and lime are materials usually used to improve soil properties. Developed methods include both surface improvement (*in situ* and using stationary mixers) and deep improvement (e.g. deep soil mixing) which result in soil lithification over a certain area, specified for that method. Increasingly often, where subsoil conditions are demanding, also hybrid foundations combining both improvement techniques are being designed [3].

High economic and environmental costs of using hydraulic binders result, however, in an intensified search for other technologies which would yield a similar outcome without the need to use large quantities of cement, for instance. One of the oldest methods in use is electroosmotic soil improvement [4,5]. Another example may be the use of low-pressure injection of silica solution to improve liquefying soils [6,7] or soil surface improvement with biopolymers [8].

Contemporary challenges and results of the research to date show that the search for alternative and environmentally-friendly ways of soil improvement is the right direction to take. As soils are frequently used as a construction material, as stated above, in particular in road and hydrotechnical construction, it seems vital to study the efficacy of biogrouting in the context of dynamic impact on soil during compaction. Therefore, the present paper undertakes to analyse biogrouting of silty soil compacted using standard energies in laboratory conditions. This study included an analysis of sample preparation technology and initial shear strength tests of the soil samples obtained.

2. Biomineralisation applications in construction

The need to give construction materials protective and binding properties in order to reduce penetration of harmful substances from the environment and leach valuable elements from natural and artificial stones – cement matrix composites, including concrete – resulted in the search for alternative conservation methods. De Muynck et al. [9] proposed an effective and environmentally-friendly technique of creating products binding stone materials. It is based on biomineralisation caused by some bacteria which in favourable microenvironmental conditions trigger extracellular precipitation of calcium carbonate in natural and artificial stone materials. The resulting product is compatible with the base material and chemically bound with the internal surface of voids which it fills out. *Bacillus* bacteria are particularly effective [10,11], as they are capable of precipitating calcium carbonate on their cells by hydrolysing urea to ammonia and carbon dioxide [12–14].

Bacillus bacteria are common in the environment and usually found in the soil but also in seawater and freshwater, hot springs, silt and surface water deposits, on the surface of plants, and in gastrointestinal tracts of some animals. Commonness of these bacteria and their high tolerance of variable temperatures, pH, and salinity are ensured by their ability to produce bacterial spores. Both the presence of endospores and cilia cells contribute to their effective distribution in the environment. Many species of the *Bacillus* genus are used in biotechnology to produce extracellular enzymes, in biosynthesis of insecticidal endotoxins and other proteins, hydrolysis of esters and transformation of steroids, as well as biodegradation of *n*-alkanes, pesticides, hydrogen cyanide, phenols, and many other environmentally toxic compounds. *Sporosarcina pasteurii* bacteria's individual trait is its ability to precipitate $CaCO_3$. Ca^{2+} is commonly known as one of the key microelements ensuring proper management of vital processes by bacteria. Metabolic processes, however, use up only a certain amount of calcium ions while the remaining amount deposits on the exterior surface of cells. When urea is added, bacteria activate urease, an enzyme hydrolysing urea to ammonia and carbon dioxide which turn into ionic forms of NH_4^+ and CO_3^{2-}, respectively. Combination of cells with Ca^{2+} accumulated extracellularly with CO_3^{2-} leads to $CaCO_3$ precipitation [15]. Currently, attempts are being made to use biodeposition in construction to fill in cracks, seal aggregates, or improve soils.

Okwadha and Li [16] who synthesised works by other authors list the following areas of application for biodeposition in construction:

- filling in structural cracks,
- improving durability of structures, for instance by self-healing of cement matrix composites,
- increasing concrete's compressive strength,
- soil improvement, including sand consolidation.

In 1990, Adolphe et al.'s research group applied for a patent for protection of ornamental stone by means of a microbially deposited calcium carbonate layer. French researchers developed a procedure to use biodeposition in field conditions consisting in spraying of decayed surfaces with a medium containing biological material, and subsequently with nutrients, in quantities and intervals depending on the stone type [9].

For concrete, biodeposition may be used in structural modification (self-reparable concrete with increased compressive strength [11,17–20] and surface modification (filling in cracks to reduce concrete permeability [9,13]).

In construction materials treated using biodeposition, *Bacillus* bacteria were found to be intensely growing which proves their vitality. A very significant level of precipitated $CaCO_3$ minerals is also noticeable, mainly in the form of calcite [16], as confirmed by the studies using scanning electron microscopy [10,21], and to a small extent vaterite, which is good because calcite crystals are the more durable form of calcium carbonate minerals.

Aside from external application to repair concrete cracks and crevices, addition of microorganisms into the concrete mix has also proven effective. Effect of biodeposition admixture of various potentials was studied by Chahal et al. [19], with the view to a possible replacement of part of the cement with fly ash and microsilica. Compressive strength, absorbability, and chloride permeability were measured, and the results were found to be dependent on concentration of the microbiological solution and type of substitute for part of the cement binding agent. Studies by Dhami et al. [22] found higher compressive strength, durability, and resistance of concrete to alkali and sulphates, improved frost resistance and water-tightness, and reduced shrinkage. Concrete's "self-treatment" ability consisting, in autonomic repair of cracks and crevices, is an issue which has received much attention recently.

Jonkers et al. [18] selected the group of alkali-resistant bacteria related to the *Bacillus* genotype and added them to the grout as a catalyst for repair processes. Fitness of these bacteria for such "treatment" is attributed to the bacteria's ability to release spores capable of withstanding high mechanical loads.

Use of biodeposition to reduce water absorption of recycled concrete aggregate was an innovation in concrete technology [21] as noticed and continued in the studies by Qiu et al. [23].

Grouting of loose sediment grains in geological conditions as a typical process in the natural environment, being an element of sediment diagenesis, mainly results from migration of solutions through the rockmass and precipitation of binding substances from