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Mechanical and microstructural properties of biogenic $CaCO_3$ deposition (MICP) on a specific volcanic sediment (unwelded Tuffs) by *Bacillus pasteurii* and *Bacillus subtilis*

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A B S T R A C T

Microbially induced calcite precipitation has garnered significant attention in recent years as a promising and environmentally friendly process for addressing sand stabilization and soil consolidation. While its potential to stabilize sand dunes and mitigate soil liquefaction is well-documented, the applicability of MICP in the consolidation of stone materials has not been thoroughly investigated. Tuffs, which are silicate-laden pyroclasts, have historical significance as hybrid materials for cement, emphasizing their importance in cultural heritage. In previous MICP applications, there has been a lack of exploration regarding the incorporation of urease-producing bacteria (UPB) into Tuffs. Consequently, the potential of MICP in substrates such as Tuffs has been largely overlooked. The primary objective of this study is to assess the feasibility of incorporating UPB into Tuffs as a consolidating agent to facilitate calcium carbonate precipitation. We aim to investigate the microstructure of the resulting polymorphs and the previously unknown mechanism of increased resistance to W-D cycles in the treated samples at the nanoscale. In this study, we compared the cementation response of Tuff when subjected to two different UPBs by evaluating changes in key parameters, including capillary water absorption (CWA), cyclic tests such as wet-dry and salt attack, and uniaxial compressive strength. Furthermore, the characteristics of crust formation were examined using FESEM, and an in-depth analysis of the microstructure of the deposited bacterial CaCO3 was conducted. The mechanism of increased W-D resistance in Tuffs reinforced by MICP has not been previously addressed by researchers. Our study demonstrated that the increase in resistance to W-D cycles was more pronounced in samples treated with *Bacillus pasteurii*. Further FESEM analysis showed the presence of *Bacillus pasteurii* spores in the nanopores of the (W-D) exposed samples. N2 adsorption analysis revealed that nanopore alteration occurred only in samples treated with *Bacillus pasteurii*. Additionally, Tuffs are prone to disjoining pressure, which occurs in nanopores. Based on these observations, we postulate that the increased resistance to W-D cycles in the samples treated with *Bacillus pasteurii* was caused by a decrease in disjoining pressure due to the recrystallization of amorphous calcium carbonate (ACC) in the nanopores of the studied Tuff.

1. Introduction

In recent years, climate change appears to be an inexorable force, with copious volumes of anthropogenic emissions, particularly CO_2, being annually released into the Earth's atmosphere. This relentless influx of emissions has led to an increasingly exacerbated greenhouse effect over the past century. Over the past 650,000 years, atmospheric CO_2 levels have surged from 180 to 300 ppm, culminating in the 21st century [1]. Fossil fuels have been the primary source of man-made CO_2 emissions, particularly since the latter half of the 18th century. Additionally, artificial binders such as cement, concrete, and mortars have seen widespread use in construction and building materials since their introduction to the United States in 1891. Fossil fuels are integral to the cement production process, as they are employed in kilns to convert limestone into CaO. The production of a single ton of cement (clinker) necessitates a substantial 2.9 GJ of energy, primarily sourced from fossil

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