Optimization of properties of soil concrete with biologically active additives

Vyacheslav Alekseev[1,2], *Sofia* Bazhenova[2*], *A.* Varosyan[2], and *A.* Sorokin[2]

[1]SEC "Underground Construction" of Research Institute "Geotechnics" named after Z.G. Ter-Martirosyan, Russian Federation
[2]Moscow State University of Civil Engineering, Moscow, Russian Federation

Abstract. This paper presents an experimental study on the modification of grouted soil (soil concrete) with biologically active additives, specifically mosses and algae, to improve material properties. Laboratory tests were conducted using three types of ultrafine cement (UFC) injected into medium sand, with and without biological additives. The results show that the inclusion of mosses and algae led to a modest increase in compressive strength, with the most notable effect observed for UFC Type 1, where strength increased from 2.4 MPa to 2.7 MPa at 180 days. Density of bio-modified samples was also slightly higher, which may be attributed to microbial-induced calcite precipitation filling pores and microcracks. Viability tests confirmed that microorganisms survived the injection and curing process when protective measures (buffering agents, hydrogels, low-heat cement) were applied. The proposed approach shows potential for self-healing properties, reduced carbon footprint, and lower long-term maintenance costs, while remaining compatible with existing construction practices. These findings position bio-modified grouted soil as a promising material for sustainable infrastructure applications.

1 Introduction

Construction today faces two interconnected challenges: reducing environmental impact and improving the durability of materials. One approach that has gained attention in recent years is the incorporation of living organisms (bacteria, mosses, and algae) into building materials [1, 2]. Although this idea may seem unconventional, it is supported by a growing body of scientific evidence. Grouted soil (sometimes referred to as soil concrete) was selected as the base material for this study. It is widely used in foundation stabilization and underground construction due to its availability and adaptability [3, 4]. The objective was to determine whether the addition of biological components could further enhance its properties. The underlying concept is straightforward. If biologically active substances are incorporated into the grout mixture, they may remain functional after the material hardens. Previous research has demonstrated that certain microorganisms can fill microcracks as they develop, thereby imparting a self-healing capability to the material [6, 7]. This feature is particularly valuable

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[*] Corresponding author: BazhenovaSI@mgsu.ru

for applications such as road pavements and building facades, where crack formation typically leads to costly repairs [8]. This remains a theoretical possibility at present; its practical realization requires further investigation. Beyond self-repair, there are environmental considerations. The use of mosses and algae instead of synthetic polymers can reduce the carbon footprint [9, 10]. Algae absorb CO_2, and vegetated surfaces contribute to temperature regulation and humidity control in urban environments [1, 2, 11]. Thus, functional benefits may accompany environmental advantages, provided the approach proves viable. Aesthetic aspects also merit attention. Grouted soils colonized by mosses or algae can be employed in green roofs, living walls, and other architectural applications that have gained popularity in recent years [8]. The goal is therefore not only to improve mechanical performance but also to enhance the visual and functional qualities of construction materials. Considerable research has been conducted on injection technologies for soil stabilization [3, 5], and a growing body of literature exists on bacterial self-healing concrete [6, 7, 9, 10]. However, the combination of these two areas—specifically the use of mosses and algae in grouted soil—has remained largely unexplored. The present study was designed to address this gap by investigating whether biological additives can be successfully incorporated into the grouting process and whether they confer measurable benefits in terms of mechanical properties and long-term durability.

2 Methods

For the preparation of grouted soil samples, we used a standard injection scheme with ultrafine cement (UFC) suspensions. Nothing too fancy - just standard procedures. The approach we developed involves introducing biological components - specifically, mosses and algae - directly into the grouting mixture [1, 2].

In our experiments, we tested both active and dormant forms of microorganisms. For algae, we selected Chlorella vulgaris. It's known for its photosynthetic activity and tolerance to variable conditions - a pretty hardy species, we've worked with it before [11]. For mosses, we used species from the genus Bryum, which are known to survive in alkaline environments [1].

The grout base consisted of ultrafine cement produced in the Chelyabinsk region (Russian Federation) based on Portland cement clinker separation [3, 15]. Three types were used in the experiments: Type 1 with particle size d98 within 9–20 µm, Type 2, and Type 3 [15]. The differences in particle size matter for injection, as we'll see later. The tested soil was medium sand with dry density 1.58 g/cm³ and particle density 2.70 g/cm³ [3].

The injection mixture also contained nutrient and stabilizing agents: a solution with nitrogen (KNO_3), phosphorus (KH_2PO_4), magnesium ($MgSO_4$), and trace elements (Fe, Zn, Cu) [12, 13]. To regulate pH and maintain moisture, we added carbonate buffer systems and hydrogels [6, 14].

One of the main challenges we faced was ensuring the viability of microorganisms during cement hydration. The pH rises to 12–13 and temperature increases [9, 10] - that's tough for any living thing. To address this, we used alkali-resistant strains (not genetically modified, just naturally tolerant ones). We also added buffering agents to locally reduce pH, incorporated hydrogels to retain moisture, and selected low-heat cements to minimize temperature rise [14].

In some test series, biological components were introduced in dried form (spores or dry biomass) and activated after placement by controlled moistening [6]. In others, active cultures were mixed directly into the suspension at temperatures between 10 and 30°C [14].

Grout injection was carried out using several methods depending on the test series: impregnation grouting at pressures up to 0.5 MPa and low flow rates, jet grouting at higher pressures (up to 50 MPa), and filler grouting for cavity filling [3, 4, 16]. For laboratory experiments, we used a unidirectional flow model (Fig. 1). It's a simple setup but it does the job. It allowed us to control injection pressure within 0.1–0.5 MPa and flow rates from 0.5 to 5 L/min [3, 15]. The setup consisted of a soil sample holder, inlet nozzle, and flange holders to maintain pressure during injection [3].

After injection, the treated samples were kept under controlled conditions. Humidity was maintained at 60–80%, temperature at 10–30°C. For photosynthetic organisms, we provided access to light [1, 11]. In some cases, we used surface covering to slow down water evaporation [6].

To check microbial activity after curing, we performed culture-based viability tests - samples were taken from the core of the material and plated on nutrient media. These tests confirmed the presence of active microorganisms immediately after curing [1, 11]. Standard plating, nothing complicated.

Over longer periods, we observed signs of biomineralization, including calcium carbonate precipitation in microcracks, which contributed to material densification [9, 10, 12]. The detailed results of mechanical testing are presented in the following section.

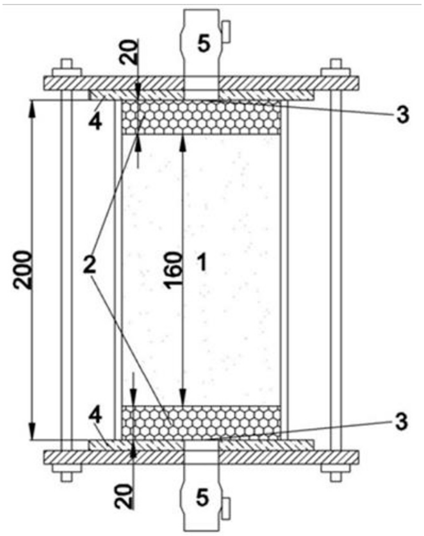

Fig. 1. Diagram of the laboratory unidirectional model (1 – tested soil, 2 – compacted aggregate, 3 – inlet nozzle mouth, 4 – flange holders, 5 – inlet nozzle)

3 Results and Discussion

We conducted a series of laboratory tests to evaluate how the addition of biological components affects the mechanical properties of grouted soil. The unconfined compressive strength was measured at 56 and 180 days for samples with and without bio-additives.
The experimental setup is shown in Fig. 2 - the left image shows the unidirectional model during processing in the lab, and the right image shows a test section before injection at one of the experimental sites.

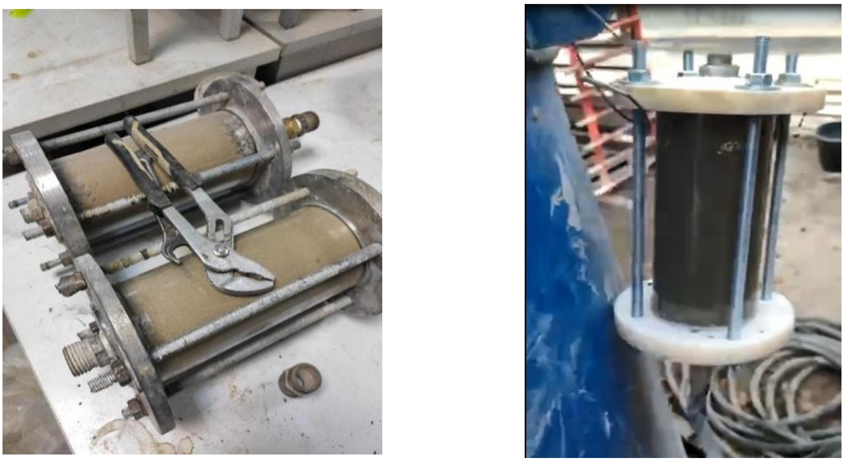

Fig. 2. Processing of the unidirectional model under laboratory conditions (left) and before injection at experimental sections of the construction site (right)

The results are summarized in Table 1. A few things stood out to us.

First, samples with biological additives consistently showed slightly higher compressive strength compared to the reference samples without bio-additives. The effect was most noticeable for UFC Type 1, where strength increased from 2.4 MPa to 2.7 MPa at 180 days. For Type 2 and Type 3, the increases were smaller but still present.

We also observed that the density of bio-modified samples was marginally higher. This might be explained by microbial-induced calcite precipitation filling some of the pores and microcracks [11, 12]. We ran these tests three times, got similar numbers each time, so we think it's reliable enough.

Table 1. Test results of grouted soil samples.

Sample No.	Composition	Density (kg/m³)	Strength at 56 days (MPa)	Strength at 180 days (MPa)
1	UFC Type 3	1560	1.1	1.6
2	UFC Type 2	1640	1.9	2.1
3	UFC Type 1	1710	2.3	2.4
4	UFC Type 3 + bio	1590	1.2	1.7
5	UFC Type 2 + bio	1690	2.0	2.2
6	UFC Type 1 + bio	1780	2.5	2.7

What is particularly interesting is that the strength gain continued between 56 and 180 days. And the increment was slightly larger for bio-modified samples. This suggests that microbial activity may still be ongoing after the initial curing period, contributing to gradual densification [9, 10].

However, we should be careful not to overinterpret these numbers. The improvements are modest. We didn't perform statistical analysis on this dataset, so the differences may not be significant. More testing is needed to confirm whether the observed effects are consistent and meaningful in practical applications [8, 13].

To check whether the microorganisms actually survived the injection and curing process, we took samples from the hardened material and cultured them. The results showed viable microorganisms in all bio-modified samples immediately after curing. This indicates that our approach to protecting them (buffering agents, hydrogels, low-heat cement) was at least partially successful [1, 11]. Whether they remain active over years of field service is another question - one that we are planning to investigate in future work.

Another observation worth mentioning is the role of the buffering agents and hydrogels. In preliminary tests without these additives, we consistently failed to detect viable microorganisms after curing. With them, survival rates improved significantly. So controlling the local environment around the microorganisms is critical - that much is clear [6, 14].

4 Conclusion

Cement grouting is a well-established technique that has been applied for decades in major infrastructure projects, including the reconstruction of Moscow Metro facilities, the restoration of the Moscow Kremlin, and the strengthening of historic buildings [3, 4, 15]. The approach proposed here does not seek to replace these conventional methods but rather to extend them by incorporating biological components that may enhance sustainability and impart self-healing characteristics. Whether such benefits are realized in practice remains a subject for further investigation.

Experimental results indicate that ultrafine cement grouts can be combined with mosses and algae without compromising mechanical performance. A modest increase in compressive strength was observed over time, which may be attributed to biomineralization or to densification resulting from the addition of hydrogels. Definitive conclusions on this point require additional study.

Viability tests confirmed that microorganisms can survive the injection and curing process when appropriate protective measures are applied, namely buffering agents, hydrogels, and low-heat cement [6, 14]. In the absence of these measures, microbial survival was not observed.

Compared with polymer-based grouting materials, the bio-modified approach offers the advantage of being non-toxic and environmentally benign [9, 11]. This characteristic alone may justify further development, even if the observed strength gains remain modest. The method also opens possibilities for aesthetic applications such as green facades.

Nevertheless, the technology remains at an early stage of development. Further research is needed to quantify self-healing efficiency, optimize nutrient formulations, and assess long-term performance under field conditions over extended periods [8, 12, 13]. Laboratory results and field performance may differ. This study represents an initial step rather than a definitive solution.

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