Geosynthetics permeated with soil bio-stabilization agent

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ABSTRACT: Despite the wide application of conventional geosynthetics in myriads of geo-technical and geo-environmental problems, the associated materials and fundamentals of installation processes remain, to a large extent, unchanged. The study presented herein introduces a novel application method which combines traditional geosynthetic elements with fast, reactive, bio-reinforcement to ultimately engineer earth-geosynthetic structures of improved resistance and durability. We integrate the mechanism of natural mineral formation within the layers of conventional geosynthetics and control the diffusion of the reactive, environmentally-friendly, solution to the surrounding geo-material. The newly formed mineral is calcite, and acts as binder between the geosynthetic layer and its surrounding soil. Two example applications are demonstrated: (i) a one-meter geosynthetic-reinforced sand column and (ii) an erosion protection barrier. The agent is stress-tested under different environmental conditions of varying temperature and water salinity to investigate its all-round performance and durability. Further, mechanical results reveal enhanced compressive strength for sand samples which are enriched with reactive polypropylene fibers. Overall, the study introduces an efficient, fast and environmentally-friendly technology towards: (i) enhancing long-term performance of earth-geosynthetic structures, (ii) reducing complex and time-consuming installation processes and (iii) allowing for targeted, fast retrofitting of existing geosynthetic-reinforced structures which lasts.

Keywords: bio-reinforcement, soil stabilization, stabilization agent, mineral formation, strength, stiffness

1 INTRODUCTION

The geosynthetic industry represents nowadays not just a branch but rather a pillar of the geo-technical and geo-engineering practice. The integration of geosynthetic elements into traditional construction practice has impacted substantially the way soil stability problems and associated risk mitigation are understood, designed and implemented in myriads of engineering applications. However, the growing presence of these materials, which claim a predominant share in shallow soil and slope stabilization applications, has not been characterized by an equally roaring progress in terms of involved materials and installation processes. Among the new materials emerged, which marked a shift in the variety of available geosynthetic-based solutions, are the Geosynthetic Clay Liners (Ruhl and Daniel 1997, Lee and Shackelford 2005). These, introduce the combined use of geo-synthetic elements with bentonite for a substantially different hydraulic and mechanical behaviour with respect to conventional geosynthetic applications. Therefore, geosynthetic materials are not necessarily perceived as purely plastic elements, acting as the sole factors of soil stabilization and/or protection. Practice suggests that there is room for efficient couplings with additives, either for overall improved performance or for extending the range of application to problems otherwise considered unsuitable for geosynthetics applications.

The study introduces a novel additive in traditional geosynthetics applications which acts a soil stabilization agent. The additive is an enzyme-based powder, extracted from the soil bacterium *Sporosarcina Pasteurii* (Yoon et al. 2001). When rehydrated (Terzis and Laloui 2018), the enzyme catalyzes the transformation of urea into bicarbonate (CO_3^{2-}) (Eq. (1)) in a cell-free environment. The produced CO_3^{2-} reacts with calcium (Ca^{2+}) to form solid calcium carbonate crystals ($CaCO_3$) (Eq. (2)). The newly mineralized crystals represent in fact, solid bonds - also referred as bridges (Venuleo et al. 2016) - among grains of soil and endow the geo-material with improved cohesion, resistance and stiffness. Figure 1 illustrates a schematic representation of the reaction, initiated by hydration of the enzymatic agent and subsequent mineral formation of calcite, which ultimately acts as binder between the geosynthetic layer and surrounding soil as well as among grains of soil in the vicinity of the geosynthetic element.

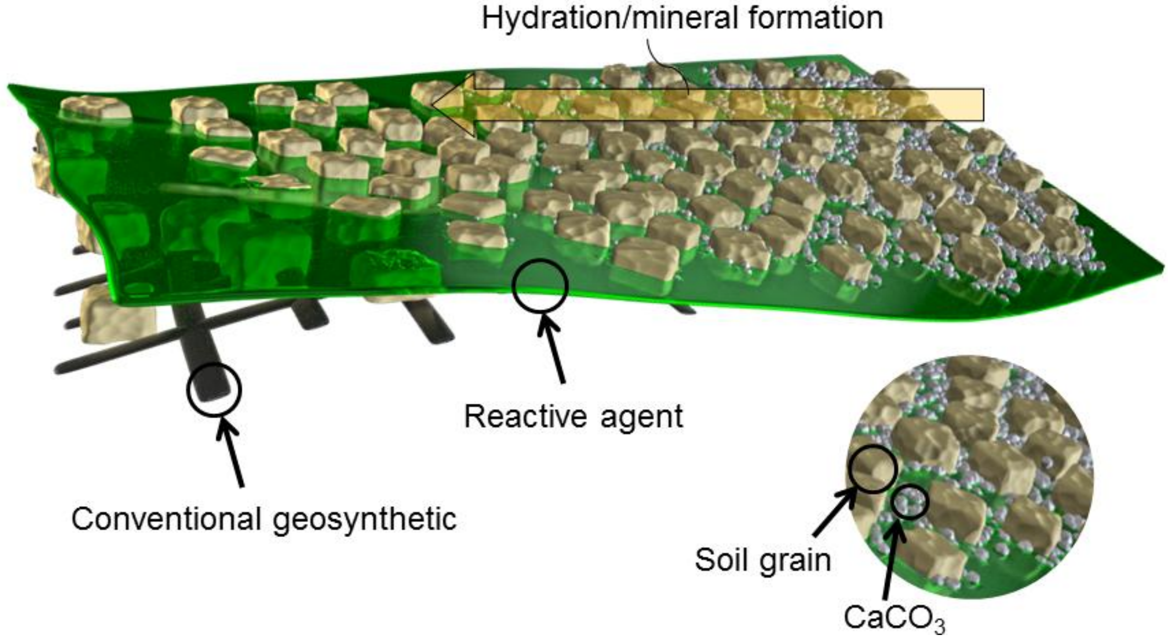

Figure 1. Schematic representation of a typical geogrid, permeated with the enzymatic bio-reinforcement agent.

$$\mathrm{CH_4N_2O} + 2H_2O \rightarrow CO_3^{2-} + 2NH_4^{+} \quad (1)$$

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

2 MATERIALS AND METHODS

A typical geosynthetic material, commercially available, was chosen on the basis of its 3D plastic structure (8 mm thick) which is attached to a fabric cloth of average pore diameters larger than 200 μm. The geosynthetic was placed at the bottom of a plastic mould and subsequently permeated with the novel bio-stabilization agent with its composition listed in Terzis and Laloui 2018. The geosynthetic was subsequently covered in 15 cm of silica sand, of mean particle size (D_{50}) equal to 390 μm. The system was further permeated with calcium and urea-rich solutions through continuous recirculation during 4 days to induce the mineralization of calcite crystals and obtain a bio-cemented material (figures 2, 3, 4). The adopted geosynthetic element and sand are shown in figure 2, in two samples representing the untreated and bio-reinforced conditions respectively. The reactive liquid agent is shown in figure 3, where mineral formation is observed in urea- and calcium-rich solution.

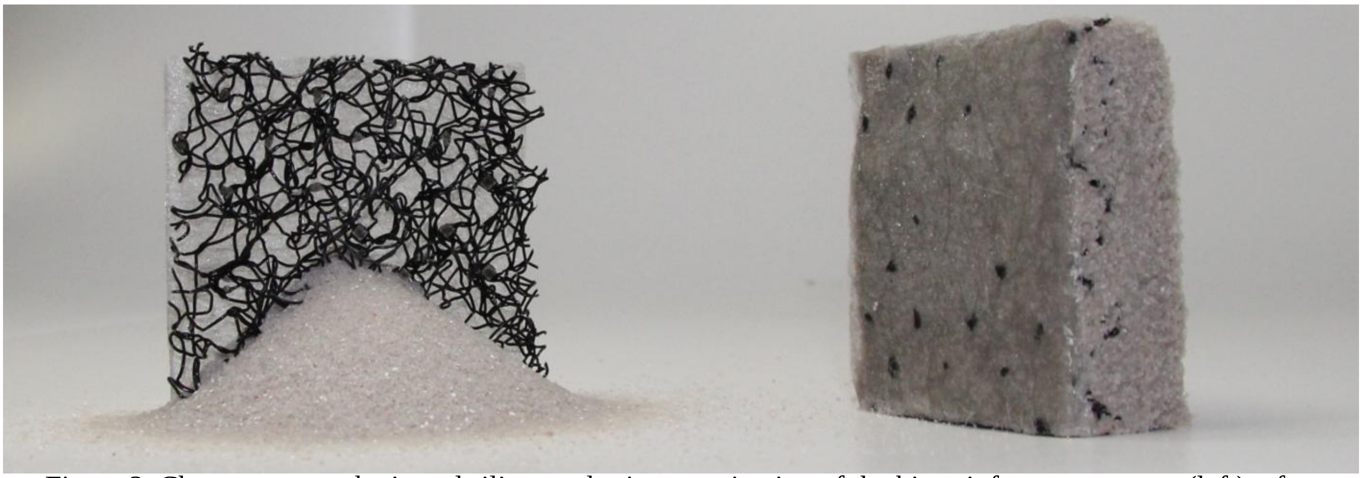

Figure 2. Chosen geo-synthetic and silica sand prior to activation of the bio-reinforcement agent (left); after infitration with reactive agent and mineral formation have taken place (right).

Figure 3. Left: calcite mineral crystals (arrows; light grey) acting as bridges among soil grains (dark grey) observed through scanning electron microscopy; middle: liquid agent reacts with urea- and calcium-rich medium to form mineral crystals of calcite (white); right: calcite mineral precipitates formed after activation of the bio-reinforcement agent, accumulated at the bottom of the flask.

The second set-up refers to a 1-meter geosynthetic-reinforced sand column. The same geosynthetic material was used as the outer element of the column, within which silica sand was compacted to produce a column with diameter of 35 cm. The bottom half meter of the column was filled with the sand shown in figure 2 (D_{50}=390 μm) and the upper half meter with silica sand having a mean particle size of 1 mm (figure 5). Subsequently, the reactive liquid solution was introduced under gravity flow from the top of the column. The effluent volume was recollected at the bottom, re-loaded with dissolved urea and calcium and recirculated through the column, continuously during 5 days. The goal of this method is to provide with a large-scale demonstration of the bio-cementation technology for geo-synthetic reinforced columns to support embankments and for slope stabilization works (Mohapatra et al. 2014). The technique of geosynthetic encased columns has been proven an efficient tool for soil stabilization in soft soils (Detert et. al 2017). Therefore, the approach adopted by the authors in the present work is considered a step towards extending the applicability of soil bio-reinforcement to problematic soft soils, a field where solutions based on traditional bio-grouting remain relatively unexplored.

Another series of tests refers to mixing sand with polypropylene fibers, rich-in bio-reinforcement agent in 50 mm x 100 mm plastic moulds to produce samples for unconfined compressive strength (UCS) tests. Results were compared with those referring to two types of silica sand: (i) fine sand (D_{50}=190 μm) and (ii) medium sand (D_{50}=390 μm). Both sands were subjected to bio-reinforcement via infiltration with (FR-MICP) and without (MICP) the use of polypropylene fibers to compare the effect of polypropylene reinforcement.

Finally, to investigate the all-round efficiency of the reactive soil stabilization agent, we alter the environmental conditions under which the agent is reactivated. More precisely we investigate a series of temperatures (5-10-15-20-28 ^{o}C) and three $NaCl_2$ contents to simulate the impact of saline water on the overall process and evaluate the applicability and efficiency of the bio-stabilization agent in coastal environments, where reactivation takes place through seawater. The efficiency determination is done indirectly via monitoring the production of NH_4^+ as an indicator of the urea degradation efficiency ((Eq. (1)) with respect to time. Details on this quantitative approach targeting the estimation of urea hydrolysis are presented in Terzis and Laloui 2018.

3 RESULTS

3.1 *Erosion protection*

The set-up described in section 2 resulted in a 15 cm-thick crust of bio-cemented soil, above the geosynthetic layer. The bio-cemented soil-geosynthetic block (figure 4) remains permeable and resists pressurized water, without erosion and wash-out of soil particles being observed. Moreover, the obtained, bio-reinforced soil retains its permeable nature, as previously reported by researchers, with the reduction in hydraulic conductivity reaching one order of magnitude for calcite contents below 10 % (Terzis 2018). The thickness of the bio-cemented block reveals at what extend the reactive agent diffuses, under low pressure infiltration, from the geosynthetic layer towards the surrounding geo-material in the short treatment period of 4 days. A sample collected from the block has been impregnated in fresh water, coming from the urban supply network, of pH equal to 6.5 for 150 days. No dissolution was observed with the sample's dry mass remaining the same. Complete dissolution of calcite is expected to occur solely under extreme acidic conditions (during acid rain for example).

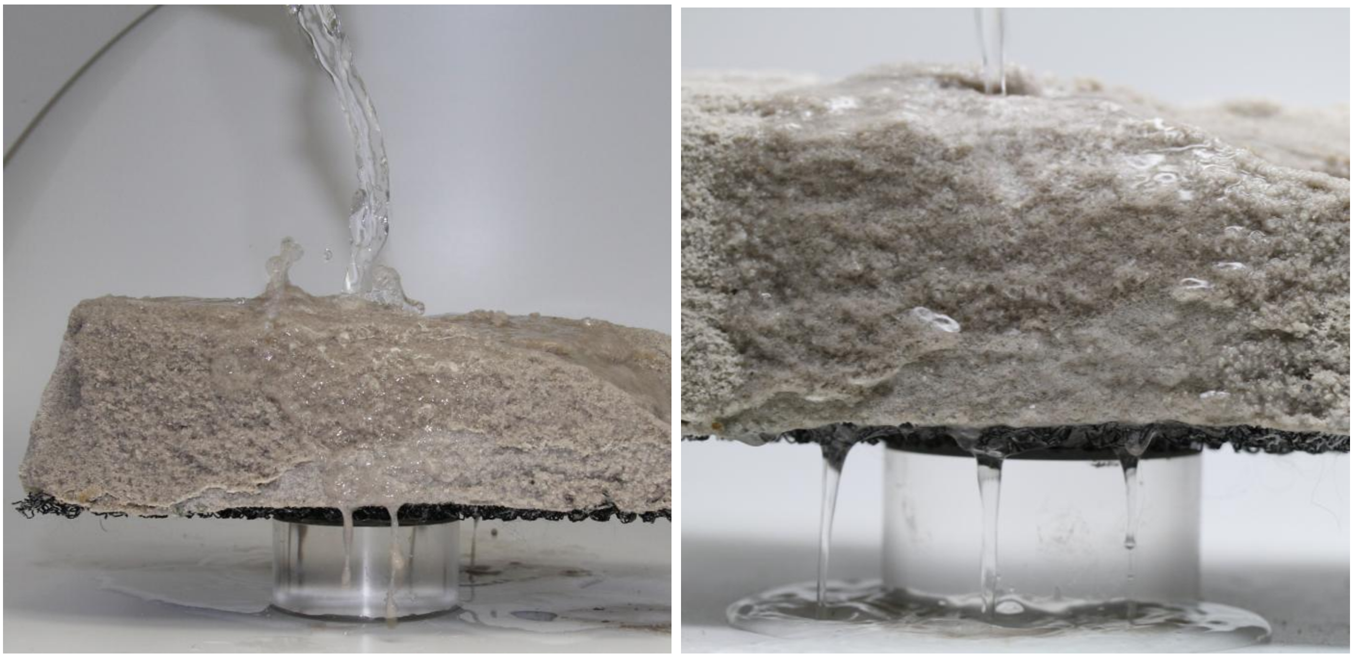

Figure 4. A 15cm-thick sand block, which was cemented via the bio-stabilization agent through the geosynthetic layer (8 mm-thick) at its bottom, resisting erosion under pressurized flow while retaining its permeability.

3.2 *Geosynthetic-reinforced column*

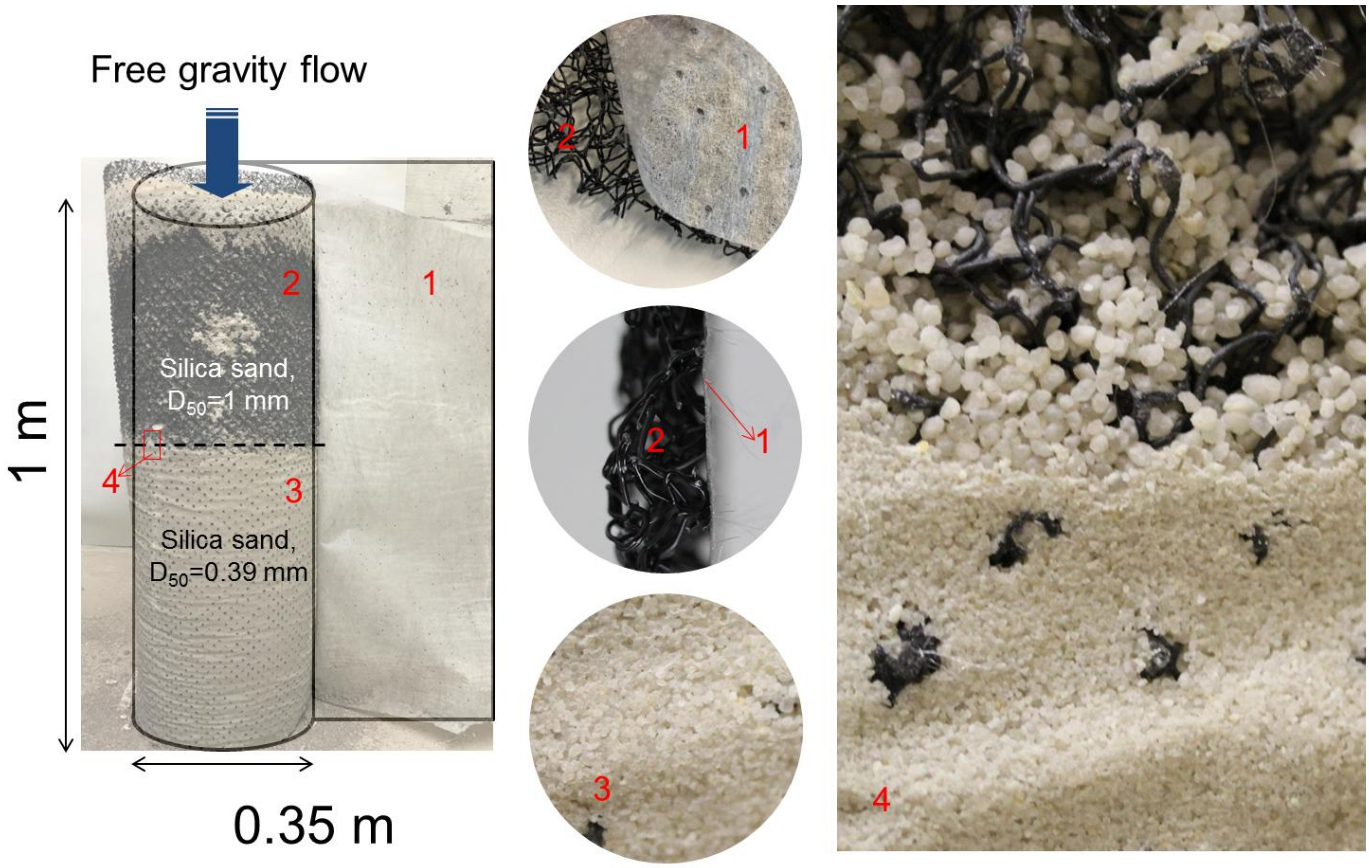

Figure 5. Left: The geosynthetic-reinforced sand column; fabric cloth detached from the plastic skeleton after bio cementation (1); 3D plastic matrix of the adopted geosynthetic (2); bio-cemented sand (3); zone between the two different types of sand which were bio-cemented through gravity flow (4).

The produced geosynthetic-reinforced column is shown in Figure 5. Interestingly, removing completely the geosynthetic was impossible with its plastic 3D matrix remaining integrated into the column after completion of bio-cementation while the fabric part was completely separated. The column retains its integrity in the absence of confinement and remains highly permeable after flushing 100 L of water. Samples were collected across the height of the column to estimate the final calcite content which ranges between 4 - 6 %. Bio-cementation is observed across the height of the column which suggests that reactant agents diffused through gravity flow, despite adopting a single infiltration source at the top of the column.

3.3 *Mechanical response*

Samples of fiber-reinforced MICP are tested under unconfined compression with results shown in Figure 6. The samples of fine- and medium-grained sand, reinforced with polypropylene fibers, are found to yield higher UCS for lower calcite contents, compared to samples produced through conventional MICP. Moreover, from the obtained post-yield response in the stress-strain plane, the material is found to exhibit less steep drop in strength, which is attributed to the resistance of the polypropylene fibers and to the fiber-soil adhesion, endowed to the material through MICP-induced cementation. Detailed results on strength and stiffness parameters are listed in Table 1 for fiber-the reinforced MICP (FR-MICP), in comparison to conventional MICP-treated specimens of higher content and to untreated samples. The unloading-reloading Young's Modulus, E_{ur}, and initial Young's Modulus, E_i, are presented, expressed as the slope of the unloading-reloading branch and that of the initial branch in the σ_1-ε_1 response respectively. It should be noted that untreated sand was tested under confinement of 30 kPa. For comparison, some preliminary work on the provision of the use of fibers, coupled with application of MICP, is presented in the work by Li et al. 2015 where polypropylene fibers were mixed with soils. Obtained results reveal UCS values which reach shy of 0.2 MPa for calcite contents between 6.6 % and 8.3 %.

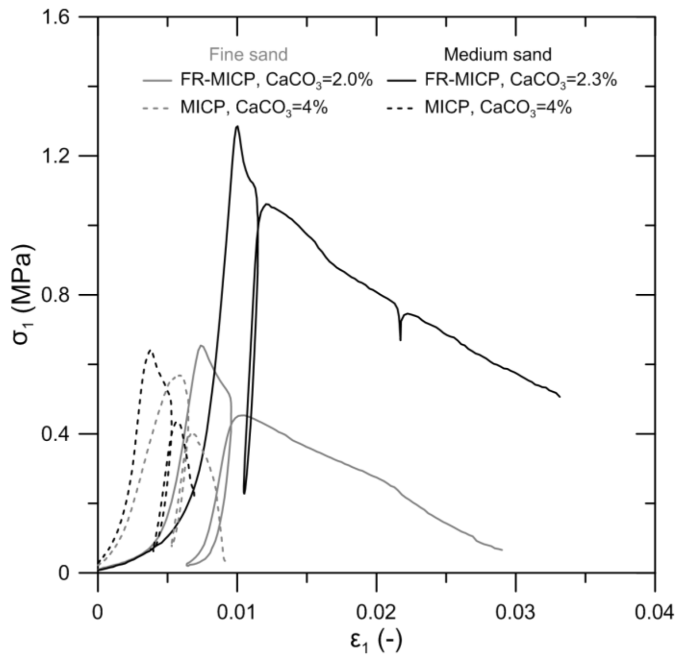

Figure 6. Stress-strain response under unconfined compression for polypropylene fiber-reinforced bio-cemented sand (FR-MICP) and conventional bio-cemented sand (MICP).

Table 1. Strength (UCS) and stiffness (E_{ur}, E_i) values, obtained for two types of sand in their untreated, Bio-cemented (MICP) and fiber-reinforced bio-cemented states (FR-MICP).

	Untreated		Bio-cemented (MICP)		Fiber Bio-cemented (FR-MICP)	
	Fine	Medium	Fine	Medium	Fine	Medium
UCS (MPa)	0	0	0.57	0.65	0.65	1.24
E_{ur} (MPa)	83	56	148	238	226	375
E_i (MPa)	12	11	262	259	192	735

3.4 *Durability of the soil-stabilization agent*

An important dimension of the proposed combined use of geosynthetics with the novel soil stabilization agent relates to the durability of the reactive mechanism under various environmental conditions. To this purpose, the agent was reactivated in two different concentrations (expressed in Optical Density, OD_{600}) under temperatures ranging from 5 to 28 ^oC and under salinity of 0-20-40 g/L. For the shake of brevity in this paper, details on the reactivation of the powder and its concentration after rehydration are explained in Terzis & Laloui (2018). The obtained results showed that for a low agent concentration (OD_{600}=0.12), increased salinity affects the speed of reaction by roughly 40%. However, the reaction is still considered fast given that for the adopted agent concentration and salinity equal to 20 g/L, a total of 1 Mol of calcite (100 g/L) was mineralized in about 74 hours, that's approximately 3 days.

Further, the agent was tested under a variety of temperatures at a lower concentration, equal to OD_{600}=0.06. Results demonstrate a linear evolution of the reaction rate. For comparison, at 5 ^oC, 1 Mol of calcite would mineralize in a total of 13 days while at 20 ^oC the same mass of calcite would be produced in less than 3.5 days. One should consider, however, that the above reaction rates refer to very low concentrations of the reactive agent. The overall agent concentration remains to be determined with respect to the nature of the foreseen engineering application and the desired mass of calcite which is necessary to improve the engineering properties of the material.

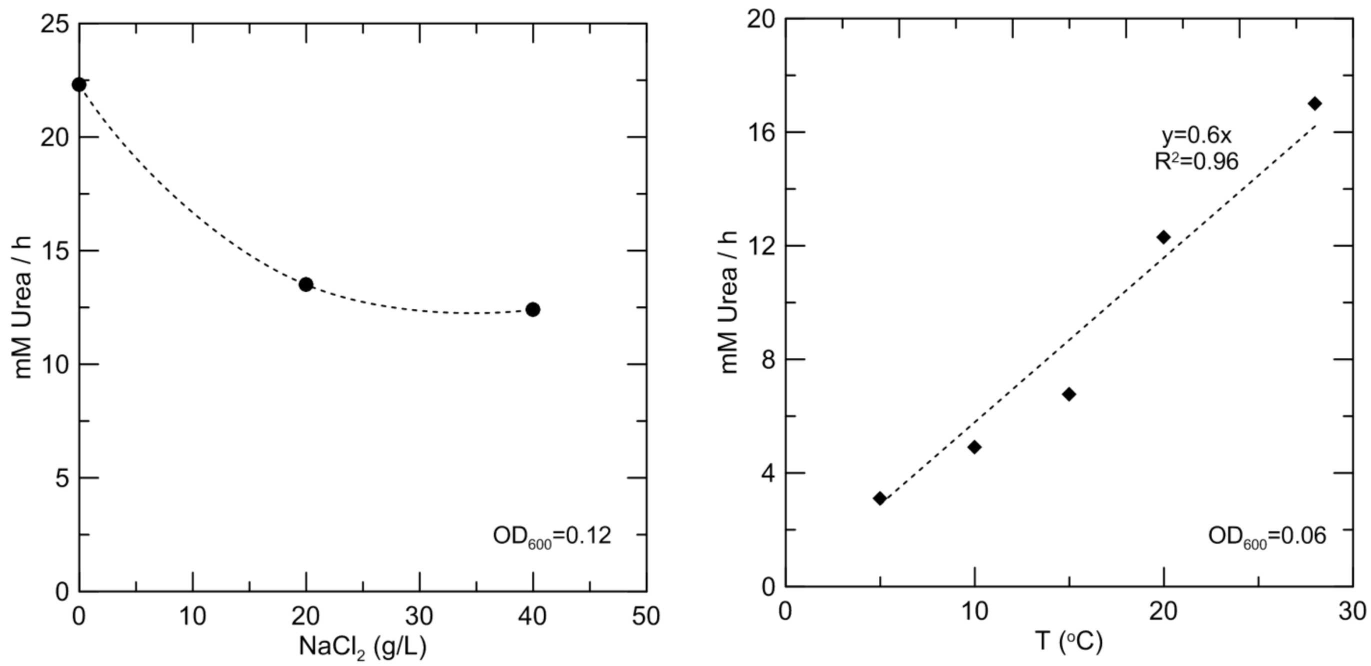

Figure 7. Soil-stabilization agent performance under various environmental conditions expressed in terms of reaction rate (mM of Urea hydrolyzed per hour); (left) increased water salinity and (right) varying temperature.

4 CONCLUSIONS

The study describes the combined use of geosynthetics with a natural soil stabilization agent which is responsible for mineral formation within soils. A conventional geosynthetic is permeated with the agent in liquid form, generating a new, improved soil-geosynthetic interaction characterized by increased adhesion. The agent is diffused to the surrounding geo-material, ultimately endowing the soil, and therefore the earth-geosynthetic structure, with enhanced performance. Two applications are showcased, targeting, respectively, engineering soil erosion barriers and enhanced geosynthetic-reinforced columns. A bio-cemented soil crust of 15 cm is obtained out of a single geosynthetic layer, of initial thickness equal to 8 mm, which was permeated with the soil stabilization agent. Further, a 1-meter tall column of geosynthetic-reinforced sand was produced in just 5 days. In addition, mechanical results reveal the increased performance of sand stabilized with polypropylene fibers, which were rich in soil stabilization agent. Finally, the agent is tested under various environmental conditions, with results suggesting an all-round efficiency under varying water salinity and temperature.

Overall, the study aims to introduce a new approach to earth-geosynthetic structures which passes through efficient, nature-based and environmentally friendly soil stabilization. The impact of the coupled use of geosynthetics and soil bio-cementation ranges, for example, from reducing the required, raw geosynthetic material used in given applications, and therefore the associated installation times and costs, to permeating existing earth-geosynthetic structures for enhancing their long-term behaviour and for retrofitting purposes.

5 ACNKWOLEDGMENTS

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