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Minimally invasive soil treatment based on bio-grout

Traitement des sols minimalement invasive à base de bio-ciment

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ABSTRACT: In recent years, significant efforts are put in the development of sustainable soil consolidation materials and methods. With the increasing awareness around the environmental impact of existing grout materials and chemical binders, biotechnologies are brought into focus and gain growing traction in groundwork operations. Herein we present the principles and application method of bio-calcification, a system which is based on soil, groundwater or marine enzymes which are able to catalyse the production of calcite replicating a natural phenomenon. The end result is mineral crystalline bridges which act as binders to improve the geotechnical properties of soils. This paper presents a comprehensive description of bio-grouts, their underlaying mechanisms as well as environmental considerations. With their waterlike rheology, bio-grouts have a wide application range and are minimally invasive, requiring only very limited injection pressures. The equipment is the same as that used in conventional cement grouting, and the reactant components are worldwide available or easily suppliable, which explains why biogrouting has nowadays become a valuable and sustainable alternative towards efficient soil treatment. Recent developments in the last years have allowed to further increase the applicability and efficiency of bio-grouts to ultimately bridge the gap between research and practice. A case study is illustrated in this paper showing the successful implementation of bio-grout for the stabilization of weakly cemented sandstone to safeguard an adjacent road segment in Switzerland.

RÉSUMÉ : Ces dernières années, des efforts importants ont été consacrés au développement de matériaux et de méthodes durables de consolidation des sols. Avec la prise de conscience croissante de l'impact environnemental des matériaux de coulis et des liants chimiques existants, les biotechnologies sont mises au point et gagnent en popularité dans les opérations géotechniques. Nous présentons ici les principes et la méthode d'application de la bio-calcification, un système basé sur des enzymes du sol, des eaux souterraines ou marines capables de catalyser la production de calcite reproduisant un phénomène naturel. Le résultat final est des ponts cristallins minéraux qui agissent comme des liants pour améliorer les propriétés géotechniques des sols. Cet article présente une description complète des bio-coulis, de leurs mécanismes sous-jacents ainsi que des considérations environnementales. Avec leur rhéologie proche de l'eau, les bio-coulis ont une large gamme d'applications et sont peu invasifs, ne nécessitant que des pressions d'injection très limitées. L'équipement est le même que celui utilisé dans les injections de ciment conventionnelles, et les composants réactifs sont disponibles dans le monde entier ou facilement disponibles, ce qui explique pourquoi la biocimentation est devenu aujourd'hui une alternative précieuse et durable vers un traitement efficace des sols. Les développements récents au cours des dernières années ont permis d'augmenter encore l'applicabilité et l'efficacité des bio-coulis pour finalement combler le fossé entre la recherche et la pratique. Une étude de cas est illustrée dans cet article montrant la mise en œuvre réussie du bio-coulis pour la stabilisation du grès faiblement cimenté pour sauvegarder un segment de route adjacent en Suisse.

KEYWORDS: bio-cementation, soil improvement, case study, in-situ monitoring

1 INTRODUCTION

Risk mitigation measures hold a catalytic role in safeguarding infrastructure and protecting the built environment against natural hazards. Such measures are applied extensively to target specific geotechnical or geo-environmental problems such as landslides, foundation retrofitting, surface erosion, seismic and liquefaction protection and embankment or road reinforcement.

Many of these works are nowadays designed based on soil mixing techniques as a means of changing the ground's composition to improve its properties. Among the most used materials are cementitious mixtures, silicates and petroleum-based resins. For all soil admixture-based solutions, the desired systems ideally minimize the required injection or mixing pressures as well as the impact on the surrounding environment while maximizing the mechanical bonding in soils and rocks. A major disadvantage of the above fluids relates to their high viscosity which requires either the application of high pressures or, in cases, high temperatures, to increase their workability and injectability. Alternatively, injection of additional, industrial fluids such as plasticizers and flocculants has been widely used to alter the mixing properties of grouts and tailor the system to the specific needs of complex works.

A critical parameter to consider hence when it comes to the design and application of ground mixing techniques is the porosity and permeability of the targeted soil mass and the range of applicable pressures. This latter is of specific interest since many works do not support the application of high pressures due to risks related to the stability of the target or adjacent formations and structures. Additionally, the lasting impact of industrial fluids on the quality of groundwater and of the underground ecosystem further raises barriers to the adoption of certain grouts and soil additives in certain zones. Cement- or lime-based fluids are known to raise the pH of the soil environment above 12 (Al-Mukhtar et al. 2010), while petroleum-based chemicals, such as polyurethanes, have been extensively investigated over their microplastic pollution potential.

Considering the above and the increasing environmental awareness and stricter regulations, there is a strong need for solutions to achieve mechanical bonding through alternative methods which minimize application pressures and are compatible within an everchanging landscape governed by environmental protection norms and guidelines.

Bio-cementation refers to a special type of soil cementation using calcium carbonate (CaCO3) acting as binder. The underlaying mechanism is carbonate conversion, through the catalyzing activity of certain soil or water microorganisms. A comprehensive review of the progress reported during the last decade in the field as well as an overview of challenges and opportunities ahead are provided in Terzis & Laloui (2019). Overall, despite significant progress reported, the technology is widely considered as an early-stage solution which needs to further prove itself before becoming mainstream. This perception is attributed mainly to the limited proof of concept provided outside of laboratories, at a scale relevant for geotechnical works. Another limiting factor is the lack of a sustainable way for treating unwanted and residual nitrous byproducts, result of the metabolic activity of micro-organisms, reported by dozens of researchers. Herein, a full-scale system is presented to provide bio-cementation which fully extracts unwanted byproducts and recycles them in an efficient way, to reduce application costs and eventually leave a calcite-rich soil, free of residual byproducts.

1.1 *Technological considerations*

The concept of bio-cementation is based on micro-organisms which can be native to soils and to the groundwater and which generate stable carbonate solutions. These micro-organisms act as mineralization agents and are utilized to generate conditions which favor the creation of mineral bridges, in the form of calcite.

More precisely, when these micro-organisms are fed with carbamide (commercially known as urea) they liberate high concentrate, dissolved carbonate (bicarbonate anions) which under the presence of calcium solutes from flowing water formulate $CaCO_3$ mineral aggregates. Often the nonpathogen and omnipresent in nature Sporosarcina Pasteurii acts as the carbonatogenic strain due to its high carbonate yield in short timeframes. Alternatively, similar concepts have been reported to achieve mineralization of calcite by utilizing either plant-extracted enzymes, which serve as the catalyzers to break down urea into carbonate or nitrifying and denitrifying bacteria, which result into $CaCO_3$ transformation through CO_2 and N-intakes. Carbamide (CH_4N_2O) is an organic soil fertilizer which is used for decades in agriculture to increase crop yield. As shown in Figure 1, nitrogen, in the form of ammonia, is combined with CO_2 for its production. In agriculture applications, nitrogen feeds crops while CO_2 is released into the atmosphere. To provide an environmentally friendly solution, the presence and handling of nitrogen needs to be properly addressed in bio-calcification works. There have been attempts to solve this problem by washing the soil with water or through dilution. However, to properly dilute nitrogen down to acceptable limits, at least 10 times the pore volume of soil in fresh water needs to be injected while the diluted nitrogen remains eventually in the surrounding soil or groundwater. Another valuable and sustainable biotech approach has been therefore developed by the authors to ultimately break the nitrogen barrier in bio-geotechnical works. This is done by introducing an ex-situ ammonia capture system to separate carbonate from nitrogen, and eventually drive carbonate into the ground while recycling nitrogen in the form of other industrial products. This circular model of supply-reuse of raw materials enables economic and sustainable bio-cementation works, which to the authors' best knowledge has not been reported in previous works. Through this system, the targeted soil remains rich in carbonate minerals and nitrogen-free.

At this point one should consider that in bio-grouting works the soil is not cemented in a strict sense, i.e. its void/fissures are not completely filled out with grout. As shown in figure 1, the crystallization of $CaCO_3$ uses and requires soil grains as crystallization nucleus points. As bio-calcification progresses, these formed crystals create bridges between grains, which leads to an increase in strength and stiffness, while the permeability is generally maintained. This latter aspect is important to the extent that it allows for reinjection if needed. Another application, where such a hydraulic characteristic is also advantageous is for slope stabilization where in this way a pore-pressure build-up is avoided economizing the installation of drainage tubes. Overall, crystallization competes in hours or a couple of days depending on the desired degree of bio-cementation and is independent of hydration or ageing phenomena. Once the reaction takes place it is irreversible and crystals remain in place, offering a locked fabric structure as geological calcite.

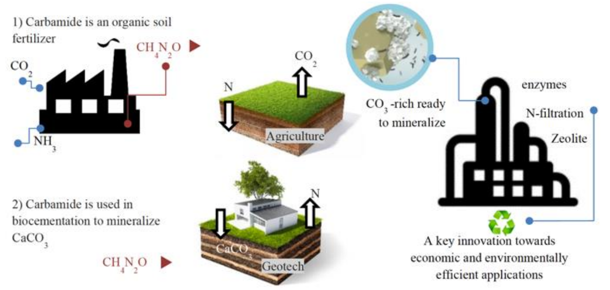

Figure 1. Overview of application of carbamide in agriculture (1) and comparison with the suggested use in geotechnical works (2) for a completely circular system of supply and revalorization.

1.2 *Application range*

One important factor when choosing a proper grout for a certain application is the penetrability, thus the capacity of the grout to enter the soil or rock to be treated. Optimally, the grout rheology shall allow to enter even smallest voids, while at the same time it shall be possible to control and limit the grout spread to the targeted zone. The grout viscosity shall therefore be carefully designed for each project, being usually characterized by something in between water-like and viscous properties.

The specific design of the bio-grout based on the total reaction time, thus binder growth rate, allows to further limit the grout spread to the desired zone. Typical soil types that can be efficiently treated by bio-grout range from silts to gravels. Very fine, cohesive soils can be treated through the coupled use of electro-osmosis and bio-cementation, whereby the solution is driven under the application of a low electric field (Terzis et al., 2020). The optimal temperature range is between 5 – 45 °C (278-318 K). Considering that water presents the carrier medium, grout temperatures below 0°C (273 K) impede the flow. For slightly lower temperatures, the bio-grout solutions might be slightly warmed up in an agitator ensuring their liquid state for the injection process. The pH of the soil should optimally be between $7 < pH < 10$. Therefore, contaminated soils require special design considerations. An important aspect of bio-grouting compared to other grout materials is, that it can be applied both in unsaturated and saturated conditions. Injections below the ground water level offer several benefits, especially by mobilizing extraction pumps, similar to those used for lowering water level in excavation pits, to better guide a flow field which carries the reactants of bio-cementation. This also makes submarine applications possible.

2 MATERIAL. SET UP & INJECTION PROCEDURE

Generally, the equipment for bio-grout is the same as for conventional cement grouting. The pump's capacity should be in the range of 0.2 to 2 bar, while often an eccentric screw pump is used. The only special equipment part required is a bioreactor, in which the enzymes and carbamide are mixed together to allow the generation of the carbonate solution under controlled conditions. The suspension is then agitated until the injection starts, in order to keep the enzymes equally dispersed. Opposed to cement grouts with their Bingham rheology, the viscosity for bio-grouts would not change, in case the agitator stops, but it remains liquid. Regarding the recycle loop, as mentioned above, this is added between the bioreactor and the injection tube to extract nitrogen and guide carbonate into the ground. This equipment fits a typical 8-feet container like those found on all construction sites.

For the grout itself, local water can be used and the calcium or reactive carbamide can be obtained from a local supplier. They come usually in 25 to 50 kg bags. The enzymes specifically designed for the project requirements are provided in dry powder or liquid form in 0.5 to 10 kg bags. The equipment includes liquid containers of 1-3 tons of high concentrate reactants for direct use. Typical tube a manchettes are used with diameter between 20-50 mm and distance among boreholes in the range of 1.5 to 5 meters.

Generally, for bio-grouting the foundation or soil mass to be treated is in a first step injected with calcium-rich water. This is important to ensure a good attachment of the next batch of carbonate on the grain-to-grain contact points. The enzymatic and carbonate -rich solution is injected in several cycles, depending on the desired outcome in terms of strength, cohesion, and stiffness. A re-injection is at any time possible since a certain permeability is always maintained.

2.1 *Grout results*

The grout results depend basically on the project requirements and initial geotechnical parameters of the material to be treated. In line with project prescriptions, the bio-grout and its injection scheme can be designed fit-to-purpose for each site and application. Key parameters for the design are the percentage of enzymes/Ca2+ on the one hand and the injection cycles on the other hand. In the following table some typical ranges of geotechnical parameters before and after injection are indicated.

Table 1. Typical improvement of geotechnical parameters by bio-grout injection

Parameter [unit]	Pre-grouting	Post-grouting
Cohesion, c [kPa]	0-10	40-150
Friction angle - φ [°]	27-32	up to 43
E-Modulus [MPa]	150-500	500-2'000
UCS [MPa]	0	up to 10
Shear wave velocity, Vs, [m/s]	300-600	up to 2'000
Hydraulic conductivity [cm/sec]	10^{-5} - 10^{-2}	10^{-7} - 10^{-3}

2.2 *Quality assessment & control*

The Quality Assessment & Control (QA/QC) scheme is generally comparable to common soil testing as performed for cement grouting. With basically no grouting pressure, the injected grout volume gives a good indication on proper penetration.

By means of extraction wells/boreholes, the CaCO3 content can be easily determined on site, giving an indication of the reaction/crystallization progress.

Other common in-situ tests, that might be considered are: (i) fluid conductivity monitoring (e.g., sampling from extraction pump); (ii) penetrometer test; (iii) geophysics; (iv) soil Compaction Testing, SCT; (iv) Ground penetration radar. Further, laboratory testing can include: (i) calcite digestion (e.g. sampling from extraction pump); (ii) typical geotechnical testing (UCS, triaxial test, oedometer); (iii) calcite digestion on cored samples.

3 APPLICATION EXAMPLE

At about 20 km northeast of Lausanne in the canton of Vaud in Switzerland, an instable slope called for stabilization interventions since it presented increased risk for the nearby cantonal road. The road cut can be distinguished basically by two geotechnical zones, one composed of weakly cemented sandstone in the upper part and a stronger molassic soil of 2 m height at the foot of the slope. The significant amount of sand and small rock blocks in the drainage ditch clearly shows the extend of the continuous erosion of the sandstone. Additionally, traces of exfoliation and fracturing can be observed in the upper zone. A detailed analysis of the sandstone revealed an initial porosity of 10%, whereby about half the soil volume is characterized by significantly increased interconnected porosity due to chemical weathering. Such soil conditions are favorable for the distribution of the mineralization agent to crystallized CaCO3.

Altogether, 1.3 tons of reactive liquid are injected in 7 boreholes. Lower boreholes cored in the more stable, molassic substrate characterized by a lower permeability serve as observation wells for the collection of effluent or the reception of sensors for the monitoring of the process. The borehole diameter is 56 mm to accommodate the injection tubes of 53 mm. Table 2 below shows the corresponding composition of the reactive agent, as it is used for this project.

Table 2. Composition of the bio-cementation agent

Element	Unit	Concentration
Carbamide	mmol	1000
Calcium Chloride	mmol	1000
S. Pasteurii	cfu/ml	1.500.000

The injection pressure is maintained between 0.3 and 0.5 bar, to avoid highly pressurized fluxes causing possible instabilities of the cliff or erosive jets within the borehole. With such low injection pressures and limited borehole depth, the installation of packers is not necessary. Just the borehole mouth is sealed to be able to maintain a certain supporting pressure in the boreholes, considering their near horizontal orientation. As expected, the highest volume is injected in the most permeable section of the upper left zone, where maximum injection pressures are sustained without any outflow observed. For the remaining boreholes, injections are stopped once an outflow is observed under lower sustained pressures. Altogether 4 injection cycles were performed with a retention period (pause in between batches to allow for reaction) between 6-8 hours to reach the required soil strength in line with the project design.

As mentioned above, generally the quality control and assessment for bio-grout applications are in line with those of conventional cement grouting. For the present case study, very detailed and elaborate investigations both, on site as well as in the laboratory are performed, in order to get a better insight in the actual grouting process and result during and after injection. Below, a selection of some special investigations is presented. To get a better understanding of the mineral morphology and its link to the estimated average estimated calcite content, sample taken from the injected facies as well as from the borehole wall are investigated microscopically (SEM). This allows to evaluate the presence, morphology and qualitative characteristics of the calcite binding particles. These characteristics are compared to those observed for the weathered, natural sandstone samples revealing distribution patterns of calcite minerals within the newly cemented structure (Figure 2).

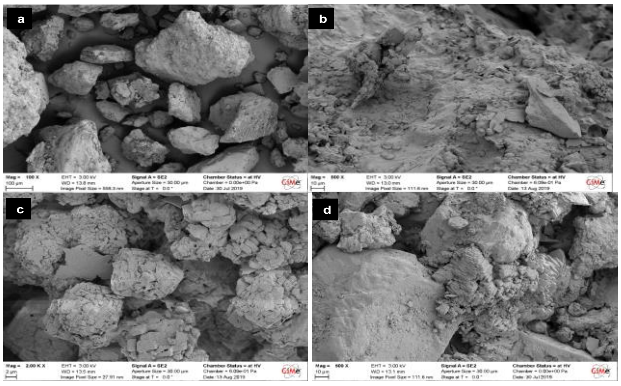

Figure 2. Sem observations. A) & b) weathered untreated oil with only little or no bonding; c) pure calcite aggregates as found on the borehole surface; d) treated soil showing hierarchical, planar features of calcite particles binding sand particles in form of mineral bridges.

For a better insight into the development of the injection and hardening processes involved in the bio-cement treatment also an extensive geophysical survey covering the entire treated zone is performed. Three-dimensional electric tomography and cross-hole seismic tomography are implemented to provide: (i) in-depth insight into the fluid propagation and reaction as well as (ii) pre- and post-mineralization spectra of the P-wave velocity field by means of a 3D mapping. This latter is used as an indication of the elastic properties and thus of the densification of the soil body, result of calcite mineralization. Finally, a ground penetrating radar campaign is also implemented to detect the location of potential waveform anomalies between the pre- and post-mineralization conditions of the targeted zone. These anomalies are then interpreted with respect to the injected reactive fluid volumes and the results from the 3D electrical and seismic tomography campaigns. More precisely, the 3D electric tomography allows to study the composition of the injected fluid and how this evolves during the reactive processes generating calcium carbonate crystals. The captured depth of change in conductivity around the injection boreholes reflects the penetration depth of the reactive fluid.

3.1 *3D Seismic tomography*

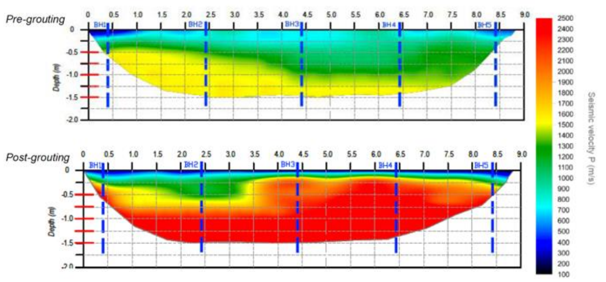

Figure 3. Example of tomographic seismic model of central section showing pre-injection (top) and post-injection (bottom) P-wave velocities.

The tomographic seismic model (Figure 3) shows an overall increase of the P-wave velocities reaching values of up to 2’500 to 3’000 m/s. These final values, which are typical for an intact limestone-like material clearly demonstrate a certain cementation caused by calcite mineralization. In particular, it can be observed that this velocity gain is more pronounced for the treated subvolumes which are fed with higher volumes of the reactive fluids. In the upper region (Figure 3), P-wave velocity maxima of 2’500 m/sec can be observed which reflects an up to 90% increase compared to the pre-treatment zones of the rock mass.

3.2 *4D Electrical monitoring with continuous data acquisition throughout the injection*

For the present works, a time-lapse electrical resistivity survey is performed to provide a quasi-real-time monitoring of the bio-cement injections in a non-destructive way. For the present study the main focus is on the measurement of changes in electrical properties in certain zones of interest over time. The survey lines are aligned in accordance with the seismic survey. The maximum examination depth is approximately 2 meters. A total of 11 ERT samplings are performed representing the pre-treatment, post-treatment and nine samplings during mineralization, one after each injection batch. Evaluating the results of electrical resistivity variation throughout the injection process is of qualitative interest, while absolute values are of lesser importance considering the complex relationship between influencing and competing factors due to solute depletion and gradual mineralization. For example, an increase in saturation, on one hand, leads to a resistivity decrease, while the structural buildup of bondings and therefore the medium’s densification, acts rather as an impediment among soil grains, and from an electrical point of view, would result into higher electrical resistivities. Looking at the absolute values of resistivity at different times during the injection process allows the determination of the resistivity boundaries as well as to follow the penetration radius of the injected reactive fluid in real time. The more pronounced change in the upper zone is related to the higher disturbance of the sandstone facies, going along with higher injection volumes. After the first 3 cycles of injections, it can be clearly seen that the resistivity increases gradually. This reflects that immediately after injection of the high ionic strength fluids, structural build-up of bonds occurs, increasing the resistivity up to 200 Ωm with a penetration radius extending beyond 1.5 m around boreholes (Figure 4). Penetrability results, however, are expected to depend heavily on local heterogeneities and fracture networks. Interestingly, the system does not yield zones of decreased resistivity, and thus increased conductivity, which would imply that residual ionic solutions remain undepleted. In this way, it is possible to state that the system reaches a steady state after each treatment cycle.

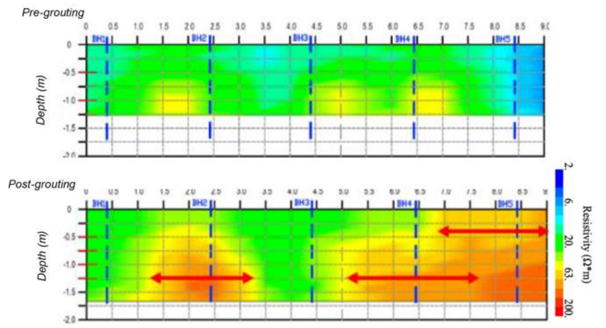

Figure 4. ERT results in terms of calculated resistivities in 3D contouring for the pre-injection condition and after the first 3 injection batches in 3D.

3.3 *Georadar survey*

A ground penetrating radar (GPR) survey is conducted to validate the consolidation induced by bio-cementation. This method uses the differences in dielectric properties of the shallow subsurface to detect and locate anomalies which reflect varying features, such as density and fracture localization. Hereby, the dielectric values of the material are affected by many factors, such as chemical composition, texture, porosity, density, and water content. Due to the high dielectric constant of water, increased water contents within the targeted layer will increase the respective dielectric values. Georadar is expected to further establish a more complete understanding, following the findings of the 3D seismic and 4D ERT campaigns, mentioned above. The survey is performed before introducing the first injection batch, as well as after the injection works are completed. The results of the GPR survey are shown in Figure 10. Before bio-mineralization takes place, and for all georadar sections, a certain reflection anomaly at a depth between 1 and 2.5 m below the surface can be observed (red lines). These geophysical anomalies might be associated with specific structural features in the cliff, characterized by higher material density. In combination with the ERT results one can confirm that the reflecting horizons are rather due to consolidation and not a sign of soil saturation. The post-mineralization GPR survey reveals an increase in the detected reflections, partially even exceeding the GPR section (green lines, Figure 5).

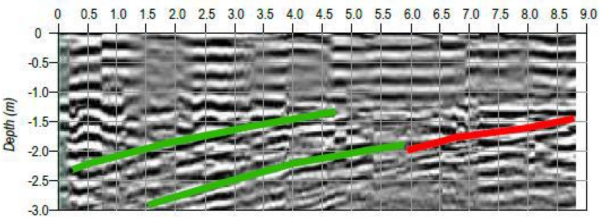

Figure 5. Ground penetration radar results example of a central section, where red lines indicate major electromagnetic anomalies before injection; green lines show major electromagnetic anomalies detected after injection.

4 CONCLUSIONS

The present paper provides an overview of bio-cementation, covering its origins in geotechnical and geo-environmental engineering as well as factors which have both, promoted or hindered its further adoption into mainstream groundworks. The authors present the various advantages offered by the technique and describe a way to overcome the handling of nitrogen, which represents the ultimate barrier of bio-cementation explaining why it has not yet been a mainstream application. A focus is the description of practical and less known details of bio-grouting, such as the large availability of required elements (Ca2+, local water, small enzyme batches); or the fact that permeability is preserved therefore the drainage capacity of soils is ensured. The presented approach of bio-cementation has reached the necessary level of maturity to take the ultimate step in the grouting field towards offering bio-cementation solutions that combine:

- Minimally invasive injections
- Improved soils with retaining permeability
- Cost-effectiveness (100-550 USD /m3 of soil stabilized)
- Low application pressures (1-3 bar), minimum vibrations
- Rapid and easy application (4-8 days)
- High structural performance
- Carbon negative applications: carbamide as additive, CO2 trapped in CaCO3
- Circular model of supply-reuse of raw materials

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