BOREAL, Bio- reinforcement of embankments by biocalcification

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Abstract. Biocalcification is a recent in-situ soil consolidation solution. It is obtained by calcite precipitation under controlled biogeochemical conditions. The industrial process, for whose implementation Soletanche Bachy holds several patents, has been validated by several experiments, initially on laboratory scale and later in situ on industrial scale under static groundwater conditions. However, it was necessary to adjust the process to make it effective for use in embankments due to the potentially high ground water flows that may be present. This is one of the main aspects addressed by the BOREAL project (Bio-reinforcement of backfilled hydraulic structures), a 4-year research and development program. Injection tests performed on a 1:1 scale in a physical model allowed for the validation of the process' feasibility in various soil types and configurations as well as under several hydraulic flow conditions. The prime objective of the process is to help mitigate erosion and liquefaction risks. The project's results are applicable to saturated and non-saturated soils. The areas of application of the process and its objectives in terms of treatment are also discussed in the article.

1 General objectives

BOREAL aims at developing a new bio-calcification process specifically for dykes that are subject to constant hydraulic load and flow, in order to improve their resistance to earthquake and internal erosion. The idea is to offer a new way to reinforce the safety of these hydraulic structures, especially regarding earthquake hazard, with:

- limited impact of the reinforcement by applying nontoxic biotechnologies to strengthen the mechanical resistance of the weak zone, without significantly changing its permeability and therefore preserving the existing fluid circulations within the structure;
- continuous operability and therefore no alteration of the economic benefit of the structure during the implementation phase (as it does not imply to empty the upstream reservoir when implemented);
- global economic efficiency: local and focused treatment, reduction of unavailability.

Biocalcification is an innovative grouting method for bio-cementing soil in situ, obtained by biological precipitation of calcite under controlled biochemical conditions. The process has been validated through numerous experiments for its application under static

conditions [1]. However, adjustments are requested for this process to be implemented on large hydraulic structures such as dykes or dams, where permanent hydraulic flows are present.

The project was divided into two phases: laboratory tests, during which all parameters could be controlled and closely monitored, and scale 1 tests realised on physical models representative of real site conditions. The first milestone of the project has confirmed the feasibility of the process at the laboratory scale (≈ 10 cm at most). The durability aspects together with the microstructural characteristics and mechanical behaviour of bio-calcified samples have also been investigated. For the second stage physical models at an intermediate scale (≈ 1 to 5 m) have been installed to simulate dikes portions under different soil configurations and hydraulic conditions. A numerical tool simulating the global behaviour of the reinforced structure has also been developed.

BOREAL was headed by Soletanche-Bachy and involved the two French leading hydropower producers (EDF and CNR), as well as laboratories from the universities of Grenoble (IGE and 3SR) and Angers (Microbiogeology Department), plus two SMEs (geophyConsult and Enoveo) dedicated to the

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mechanical and environmental characterisation of the structures to be treated.

It was certified by Axelera (Chemistry and Environment competitive cluster) as well as by the SAFE cluster (focused on the management of risks). It is supported by the French FUI (French Inter-Ministry Fund).

The project started in 2014 and ended in December 2018.

2 Biocalcification principle

Biocalcification – or bio cementation - is a new injection principle used for ground consolidation. It relies on the enzymatic hydrolysis of urea and leads to the precipitation of calcite in situ [2]. The reaction is governed by an enzymatic reaction via bacteria such as *Sporosarcina pasteurii*, which can decompose urea ($(\text{NH}_2)_2\text{CO}$) into ammonium (NH_4^+) and carbonate (CO_3^{2-}). This chemical component will participate in the composition of the final product (calcite: CaCO_3) by reacting with a calcium source. This phenomenon can be reproduced within soils, by the injection of the ureolytic bacteria and chemical reactants (Urea + calcium source).

Fig. 1. Biocalcification reaction principle

Fig. 2. SEM Image of calcite bridges and porosity.

This phenomenon plays a considerable role in increasing the mechanical strength of the treated soils, by bounding soil grains together with the precipitation of the calcite [3]. Different studies have been performed to explore the increase of the mechanical strength of the soils treated by MICP. These studies show a significant increase in shear strength of bio-mediated soils, where the calcite precipitates preferentially at the inter-granular contacts [4] which increases the amount of the cohesive contact surface between grains, thus the cohesion and the strength of the soil.

Soletanche Bachy holds several patents for implementing the process at industrial scale, based on the use of non-pathogenic bacteria in a natural environment [5]. The injected fluids, through bacterial suspension and calcifying solution, are injected by gravity or under a very low pressure as their viscosity is close to that of water. A very interesting characteristic of the process is that it allows to keep the porosity open without any significant changes to the ground permeability after treatment, conversely to the other injection processes.

Fig. 3. Biocalcis applications ranges.

The Biocalcis process covers all the steps of its implementation, from the bacterial culture phase to the injection on site and the management and control of all the calcification fluids.

The typical applications for the process are:

- Reinforcement of soils in view of reducing active earth pressure or increasing passive earth pressure and other strengthening applications. For example, for the deepening of an existing maritime structure, it could be an interesting alternative for reducing active earth pressure on sites with high constraints due to the presence of crossed tie-rods.

- Anti-liquefaction soil treatment: it is possible to mitigate liquefaction risks in loose sands by increasing their undrained shear strength C_u . For this application, C_u of some tens of kPa would be sufficient. The permeability being unchanged after treatment, there is no obstacle to the dissipation of pore pressure during the occurrence of a seism.

- Treatments against erosion: washout of fine soil particles can be stopped to prevent internal erosion (between silts and gravels for example), or to avoid suffusion problems.

- Application of the process on dikes and their foundation to mitigate liquefaction and erosion problems is the goal of the BOREAL project. In both cases, adaptations of the grouting parameters are necessary to make the treatment efficient when applied under continuous hydraulic flows and high gradients.

3 Results of small scale studies

The aims of the laboratory studies that were performed on small scale samples were the determination of the mechanical performances, the study of microstructural and physical properties, the evaluation of the resistance

to erosion and the assessment of physical and chemical durability. Finally, the environmental impact of bacteria and the biocalcification process was also determined to define a study methodology that could be used at a larger scale.

3.1 Strength properties

The objective was to analyse the effect of biocementation on the mechanical behaviour of sand, mainly its shear strength parameters (cohesion, maximum and residual friction angles, dilatancy angle) but also the pre-failure characteristics (elastic modulus). SEM and X-ray micro-tomography observations have also been performed on several bio-cemented sand specimens in order to explore in a qualitative way the change of the microstructure, the spatial distribution of calcite crystals and their morphology, considering samples with calcite contents ranging from 0 to 11.9%. The permeability of each specimen has also been measured. The main conclusions of this experimental campaign are summarised hereafter.

The permeability of the treated samples is inversely proportional to the calcite amount. For small amounts of calcite, the permeability is slightly reduced, by around 20%, compared to untreated sand samples. This decrease exceeds 75% for high amounts of calcite (12.4%). The performed triaxial tests have shown an increase of the strength as well as the initial stiffness of bio-cemented sand compared to untreated material. This increase is due to the boost in the contact cohesion, which can hamper the deformation of the solid skeleton. The volumetric behavior changes direction near the peak, passing from contractive to dilative. Regarding the residual strength, treated sand reaches an ultimate strength state that is slightly higher than that of untreated sand. The elastic modulus E and the cohesion show an exponential relationship with the amount of calcite. This is mainly due to the evolution of the contact surface, the solid fraction and the coordination number inside the treated specimen. Overall linear evolutions of the peak and residual friction angle are observed with the level of cementation (they can be interpreted as an effect of the densification, the cohesion and modification of the particle size distribution as well as an additional roughness generated by calcite crystals distributed on grain surfaces, and persistence of cemented sand grains agglomerates).

Fig. 4. Example of cohesion versus calcite content.

3.2 3D x-ray Microtomography

The exploration in a quantitative way of the treated soils microstructure is necessary to understand the evolution of the mechanical and physical properties of the bio-cemented soils. Different sand specimens with various calcification levels have been observed in the European Synchrotron Radiation Facility (ESRF) at a very low resolution in order to (i) observe the distribution of the calcite at pore scale and (ii) characterize the evolution of the microstructural (volume fraction of calcite, contact surface area, coordination number, specific surface area...) and physical properties (permeability) of bio-cemented sand depending on the cementation level. All these properties were computed on 3D images of sub-samples at high resolution using synchrotron x-ray tomography and compared with experimental data, when available. All the comparisons showed a good correspondence between numerical and experimental data proving the validity of the proposed method to treat the 3D images and to separate the three different phases (sand, calcite, pore). All these numerical and experimental results show that the biocementation process creates a thin layer of calcite on the sand grains. In average, the thickness of this layer is about 6 to 7 microns, i.e. the order of one layer of calcite crystals. In addition, the contact surface area and the coordination number both increase corresponding to the creation of a few number of contacts and simultaneously a large concentration of calcite at the level of pre-existing contacts between grains [6].

Fig. 5. 3D structure of a biocemented sample.

3.3 Erosion tests on calcified samples

A set of Contact Erosion Tests (CET) has been performed on treated Fontainebleau sand samples with a calcite content ranging between 0% and 7% [7]. The untreated material presents a high sensitivity to contact erosion with a critical velocity of 10^{-2} m/s. For high and intermediate calcite contents (between 2% and 7%), no erosion was observed at the apparatus' maximum flow rate (corresponding to a velocity of $7 \cdot 10^{-2}$ m/s). The increase of the critical velocity is thus higher than 700%. At low calcite contents (between 1% and 2%), a small increase on the critical velocity could be observed (up to +50%) but the heterogeneous distribution of grain

binding crystals leads to a large discrepancy between the results.

Hole Erosion Test and Jet Erosion Test have also been performed on the Fontainebleau sand [8] with different calcite contents (between 5% and 10%). Resistance to erosion is improved by the treatment for both tests. The treated material is “Resistant” in the classification proposed by Hanson for JET results in comparison with a classification “Very erodible” for the untreated material. HET is not feasible on the untreated material (initial collapse of the sample) but treated material can be tested and is classified with a velocity of erosion “Moderately rapid” according to Fell classification.

Fig. 6. Erosion resistance of Fontainebleau sand.

3.4 Durability

By creating calcite bridges between the grains, biocalcification increases the shear strength of an initially non-cohesive granular matrix. The obtained cohesion may be weakened over the long term by the dissolution of the precipitated calcite bridges. An experimental and theoretical study was performed, at three different scales (1) a meso-scale study, with circulation of aggressive waters through columns of calcified sands, using under-saturated water in terms of calcite content, followed by tri-axial tests to gather information on the alteration of the mechanical properties. (2) a micro-study (X-ray tomography), by comparing the state of the grains before and after percolation by aggressive waters, to control the physical state of the calcified contacts created by the biocalcification process. This will allow for a better understanding of the causes of the mechanical properties' deterioration. (3) a carbonate-chemistry based modelling study of the aging process under dynamic conditions. This helped to identify the main physical and chemical parameters that control the ageing process at short and long-time scales.

In summary, durability tests put in evidence the specific behaviour of calcite. The kinetics of calcite dissolution are very fast and the limit of solubility is very rapidly reached. This phenomenon highlighted during columns experiments and it also exists in natural environment in continental waters. It is easy to demonstrate by solubility calculation that most of the continental waters in contact with sedimentary rocks are saturated in terms of calcite. This conclusion is

reassuring as in the majority of cases it will prevent the potential weakening of biocalcified structures provoked by dissolution of the calcareous mass. For a global approach, it seems necessary to determine the saturation index of the water that will percolate through the treated area, measured over a 24-hour period in the hot season, as the diurnal and seasonal cycling of the respiration process generates temporary variations of key chemical parameters in surface waters.

3.5 Environmental aspects

The assessment of the environmental performance of the technology was carried out in two ways. The first aimed to determine the fate and environmental impact of the bacteria injected during the process and the second to assess the impact of the products (calcifying medium: urea and CaCl_2) and co-products (eg, NH_4Cl) on the environment (eg, water systems), using reference organisms and indigenous microorganisms as targets (bio-indicators).

In order to follow the fate of the bacteria injected during the process, specific molecular biomarkers (DNA) have been defined from the strain used in the process (*Sporosarcina pasteurii* referenced ATCC11859 / DSM33). These biomarkers (tracers) allow to determine the number and to follow the activity of the bacteria injected both in the zone of rejection and at different points distant from this zone, in the environment. The impact of the injected bacteria on indigenous microbial communities was determined using genetic fingerprinting approaches conventionally used in molecular biology (eg, RISA). The impact of the products and co-products was carried out under laboratory conditions during the pilot tests carried out at the CNR by exposing a receiving environment (sediments from a real site) to the effluents of the process. The work carried out to date has shown that the process has no effect in the tested conditions, by observing microorganisms breathing (O_2 consumption) as shown in Figure 7.

Fig. 7. Examples of impact from Boreal fluids.

4 Tests in physical models

The BOREAL project includes physical models using an experimental device that previously existed in the CACOH (Centre d'Analyse Comportementale des Ouvrages Hydrauliques) laboratory at CNR. Designed as part of the ERINOH project (for internal erosion of

hydraulic structure), this system consists of a reinforced concrete structure 8 m long, 4 m wide and 2.2 m high, which can be closed to its downstream end by metal cofferdams [9]. This device makes it possible to impose a constant hydraulic load difference (up to 3 m) to the volume of soil that is tested.

Two typologies of tests were selected (Table 1). For "Type A", the model is filled with only one type of soil. This type of test was dedicated to the validation of numerical models and injection feasibility tests for soils of different permeabilities and nature (Figure 4). For "Type B", a more permeable foundation layer is associated with a less permeable soil. This configuration aims to test the efficiency of the treatment in the vicinity of the interface zones (often encountered at EDF and CNR dykes and which are supposedly at the origin of most of the internal erosion pathologies). The tests consisted of treating a mass of soil under continuous gradient (= water flow) and afterwards determining the dimensions of the treated volume as well as the mechanical, hydraulic and chemical characteristics of the calcified blocks. From these data, the homogeneity of the treatment could be evaluated and during deconstruction treated samples were collected for characterisations at sample scale.

Table 1. Synthesis of the physical models and main outcomes

Test name	Soils	Main outcomes
A1	Fontainebleau sand	<ul style="list-style-type: none"> Validation of the numerical model on a homogeneous sandy soil Collection of samples for characterization Typical values of mechanical, hydraulic and chemical parameters of treated soil
A3	Chavanay sandy gravel	<ul style="list-style-type: none"> Validation of the possibility to treat gap graded heterogeneous soil
A3bis	Chavanay sandy gravel	<ul style="list-style-type: none"> Evaluation of the treatment with high velocities
B1	0/4 mm sand above 10/20 mm clean gravel	<ul style="list-style-type: none"> Treatment of a sandy soil above a gravelly foundation
B2	Bourg-Lès-Valence silty sands above 0/22,4mm sandy gravel	<ul style="list-style-type: none"> Treatment of sandy gravels Limited radius in silty sands

The grouting parameters, i.e. concentration in bacteria and calcifying solutions, injection flow rates of both fluids, were modelled by Soletanche Bachy with an in house numerical tool developed in Comsol Multiphysics, using specific set of parameters combining hydraulic conditions and biochemical reactions based on laboratory experiments. Each cycle of injection consisted of one phase of bacteria injection immediately followed

by one phase of calcifying solution injection. A single and a double cycle were applied in each test, on distinct boreholes, to check the influence of the concentration on the calcification level. During all the injection tests, samples of fluids were taken inside the physical model and at the outlet to follow specific biocalcification parameters such as OD₆₀₀, specific urease activity and hydrolyse rates. Samples of exhaust fluid were also regularly taken with an automatic sampler in order to carry out environmental impact assessment during the injection process and the percolation through the calcified mass.

The five tests performed under different hydraulic conditions yielded in the successful calcification of a volume of about 10 m³ each [10].

Injection in the fine-grained sand allowed for the validation of the design model built in Comsol to predict calcification results according to injection parameters. Experimental results fitted very well with predicted results regarding shape of the obtained calcified bulb and calcite content (Fig 8).

Fig. 8. In situ calcified A1 block vs modelling.

A good correlation was found between penetrometer tests and calcite content but at this stage it can only be considered as qualitative information showing an increase in strength after treatment (from ~2 MPa before to >50 MPa after treatment). Seismic measurements before and after treatment also showed a significant increase in shear velocity V_s (from 250-300 m/s before to 500-1400 m/s after treatment,) and confirmed that the technology can be employed for controlling end results. This is of particular importance for anti-liquefaction applications. Tests A3 and A3bis with a sandy gravel validated the possibility to treat this heterogeneous gap graded soil even under natural velocities up to 10-3 m/s. Direct comparisons between numerical predictions and experiments were difficult due to the high natural calcite content in this material: calcite content added by the treatment is complex to measure precisely. However, from observations during dismantling and the results of CPT and seismic velocity measurements the treated zone could be delimited and characterized. Test B1 showed that the treatment can be applied to calcify a sandy core just above a gravelly foundation, with natural velocities in the foundation up to ~10-3 m/s. In this configuration where contact erosion can be suspected, the treatment of the fine soil could provide a promising mitigation solution.

Fig. 9. Calcified block after excavation in 0/4 mm sand, above the gravelly foundation (B1).

Fig. 10. Results of a dynamic penetrometer test (B1).

5 Conclusion

The results and conclusions of the BOREAL project validated the industrial calcification formulations and process and highlighted its applicability to sites under permanent water flow. They illustrated on different configurations the possibilities of the method and provided characteristic mechanical and hydraulic values that can be obtained on the treated soil. Limits of the method were challenged by testing very heterogeneous gap graded soil and high flow velocities (10^{-3} m/s). The treated zones obtained for these severe conditions were less homogenous than those in the uniform fine sand but still satisfactory in terms of achieved characteristics. These experiments also underlined that conventional investigation means such as static and dynamic penetrometer, as well as seismic measurements can be used to control on site the quality of the treatment.

Two real site tests are now in preparation with CNR and EDF to validate the process in situ.

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