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Biocementation treatment of a Portuguese motorway slope to prevent ravine formation

Traitement par biocimentation d'un talus d'une autoroute portugaise pour éviter l'érosion par ravinement

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ABSTRACT: Biocementation is an environmentally sustainable technique for soil improvement, in which the precipitation of calcium carbonate is promoted by using biological agents such as bacteria or enzymes. The precipitated calcium carbonate, or biocement, is responsible for soils strength and stiffness increment due to the bonds created between the particles, and for reducing the permeability caused by pore clogging. The shallow treatment of sandy soils to increase resistance to the formation of ravines is a new application. This treatment was carried out in a real case to avoid ravines caused by rain and is being monitored over time as part of an ongoing project of Instituto Superior Técnico funded by FCT (ref. PTDC/ECI-EGC/1086/2021). This case-study is an excavation slope in sandy soil on the A13 Motorway managed by Brisa. The treatment was carried out by Rodio Portugal, from the Soletanche-Bachy group, who provided the technology to inject into the soil the treatment fluids with bacteria. The first monitoring data are presented, consisting in the amounts of calcium carbonate measured right after treatment and after the first heavy rains, with encouraging results.

RÉSUMÉ: La biocimentation est une technique écologiquement durable d'amélioration des sols, dans laquelle la précipitation du carbonate de calcium est favorisée par l'utilisation d'agents biologiques tels que des bactéries ou des enzymes. Le carbonate de calcium précipité, ou biociment, est responsable de l'augmentation de la résistance et de la rigidité des sols en raison des liaisons créées entre les particules, et de la réduction de la perméabilité causée par le colmatage des pores. Le traitement superficiel des sols sableux pour augmenter la résistance à l'érosion par ravinement est une nouvelle application. Ce traitement a été réalisé dans un cas réel pour éviter les ravins causés par la pluie et est surveillé au fil du temps dans le cadre d'un projet en cours de l'Instituto Superior Técnico financé par FCT (réf. PTDC/ECI-EGC/1086 /2021). Cette étude de cas est une pente d'excavation en sol sableux sur l'autoroute A13 gérée par Brisa. Le traitement a été réalisé par Rodio Portugal, du groupe Soletanche-Bachy, qui a fourni la technologie pour injecter dans le sol les fluides de traitement contenant des bactéries. Les premières données de suivi sont présentées, constituées des quantités de carbonate de calcium mesurées juste après le traitement et après les premières fortes pluies, avec des résultats encourageants.

Keywords: Biocementation; excavation slope; ravines; monitoring; calcium carbonate.

1 INTRODUCTION

Biocementation is an environmentally sustainable technique for soil improvement, in which the precipitation of calcium carbonate is promoted by using biological agents such as bacteria or enzymes. The precipitated calcium carbonate, or biocement, is responsible for soils strength and stiffness increment due to the bonds created between the particles, and for reducing the permeability caused by pore clogging.

Non-pathogenic urease-producing bacteria are used for the treatment. The urease enzyme from the bacteria catalyses the hydrolysis of urea (Eq. 1), and calcium carbonate (biocement) precipitates in the presence of a source of calcium (Eq. 2):

$$CO(NH_2)_2 + 2H_2O \rightarrow 2NH_4^+ + CO_3^{2-} \quad (1)$$

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

This treatment is used in many geotechnical applications, for example to increase load bearing capacity of foundations, provide soil resistance to erosion and against liquefaction, and to reduce the collapse potential of soils (see for example Al Qabany *et al.* 2012). The shallow treatment of sandy soils to increase resistance to the formation of ravines is a recent application tested in small-scale laboratory tests (Fernandez and Cardoso, 2022), and was applied in a real slope in Portugal to investigate the durability of the treatment, in the scope of the ongoing project of Instituto Superior Técnico funded by the Portuguese Foundation for Science and Technology (ref. PTDC/ECI-EGC/1086/2021). This case-study is an excavation slope of the A13 Motorway, managed by Brisa. The treatment was carried out by Rodio Portugal, from the Soletanche-Bachy group, who provided the bacteria. The treatment applied in the slope and the first monitoring data are presented in this paper.

2 CASE STUDY

2.1 Overview

The slope treated (Figure 1) is located at A13 Motorway near Benavente, 40 km from Lisbon, Portugal. It was selected to meet the following criteria: excavated in a sandy geological foundation, maximum 6 m in height, slope smaller than 30º, no accentuated signs of ravine, and be accessible from the top.

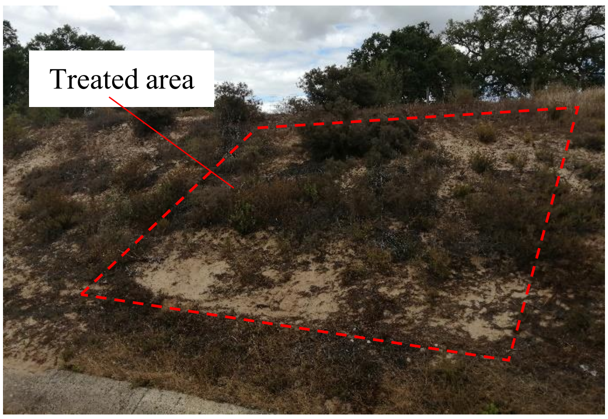

Figure 1. Slope before the treatment and treated area.

The soil of the treated area classifies as a well graded sand (SW) with 2% non-plastic fines and no gravel. The average dry unit weight is 15.5 kN/m^3 and the permeability measured was 2.4x10^{-4} m/s.

2.2 Bacteria and feeding solutions

Bacteria *Sporoscarcina Pasteurii* in lyophilized form were used, supplied by Soletanche-Bachy. They were mixed with tap water. The feeding solution was prepared also with tap water, using equal concentrations of urea and calcium chloride (0.5 M each).

2.3 Treatment

The area treated was the upper part of the slope (around 6 m × 6 m, see Figure 1), being left an untreated horizontal stripe (1 m width) in the bottom, which would receive the treatment fluids that would not be infiltrated in the treated area.

The treated area was divided into two vertical stripes to test two different methodologies: injection and irrigation was applied in the right side, and irrigation was applied in left side (Figure 2). The irrigation would treat only a surface layer, with a thickness expected to be between 0.08 and 0.10m. The injection was done using pipes (5 columns and 12 rows) placed at a depth of 0.5 m. The treatment protocol followed was identical for both methods. It was designed to reach the minimum percentage of calcium carbonate of 4%. The treatment was applied in September 2022 by Rodio Portugal and had the duration of 5 days.

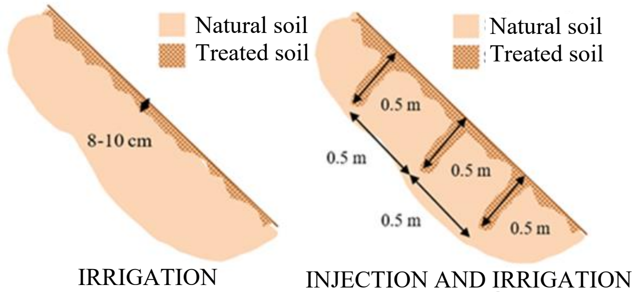

Figure 2. Treatment methods adopted for the two vertical strips of the slope.

The construction site was organized in the first day, being the slope surface levelled and the injection pipes installed (Figure 3). A plastic membrane was placed in the bottom to collect the effluent fluids during the treatment and from the final washing.

The treatment was applied in the following three days, with two applications in each day. It consisted in adding the bacteria solution to the soil followed, one hour later, by the addition of the feeding solution. These fluids were pumped from the mixer where they were prepared (Figure 3) into the injection pipes with valves. The injections were applied in the 5 pipes of each row, starting in the top of the slope, and were controlled pipe by pipe.

Figure 3. Installation of the injection pipes (left) and mixer used to prepare the bacteria and feeding fluids (right).

In the last day, the slope was washed with water through injection and irrigation and the plastic membrane at the bottom was removed.

2.4 Monitoring

The monitoring campaigns took place on average every two months, from September 2022 to July 2023, knowing that the treated slope will be observed for at least two years. A 5x5 grid, with dimensions 5.5 m x 5.5 m, was created to define the positions to extract small soil samples for measuring the percentage of calcium carbonate in the laboratory (Figure 4). These samples were extracted to 3 cm depth.

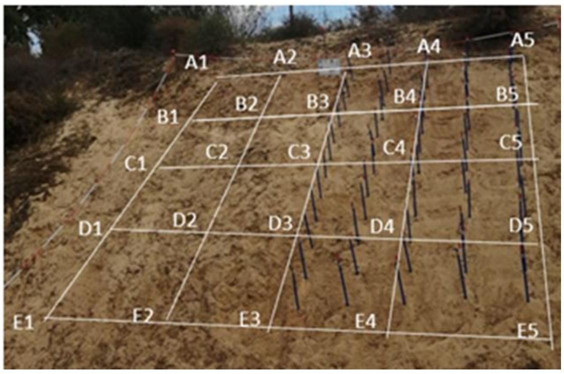

Figure 4. Grid defined for sampling during monitoring.

The percentage of calcium carbonate (*$\%CaCO_3$*) is given by Eq. 3., where m_{before} is the initial weight of the dried samples, and m_{after} is the weight of the same samples dried after being washed with hydrochloric acid (0.5 M):

$$\%CaCO_3 = \frac{m_{after} - m_{before}}{m_{before}} \qquad (3)$$

3 CALCIUM CARBONATE DISTRIBUTION

The percentage of calcium carbonate measured in the samples collected allowed plotting the calcium carbonate distribution maps presented in Figure 5 using the Surfer® program (Golden Software, 2023).

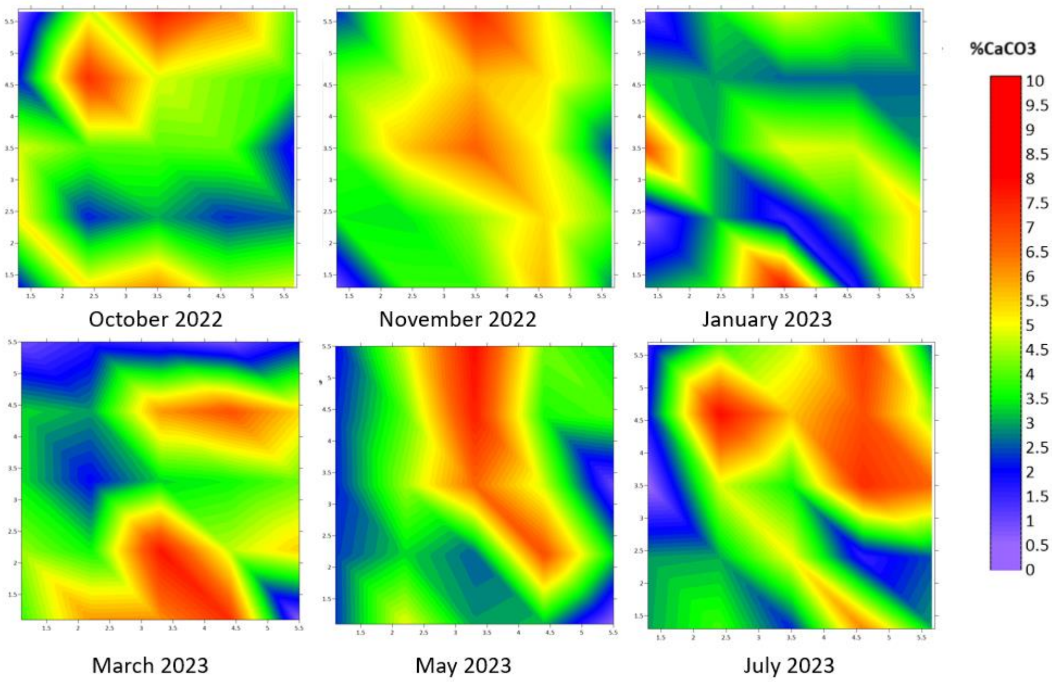

Figure 5. Distribution maps of the percentage of calcium carbonate in the treated area.

It can be seen that the treatment was heterogeneous and the %$CaCO_3$ varied after successive sampling along time in each position. Some calcium carbonate was accumulated in the central zone, mostly at the top, where the treatment was applied by irrigation and injection. The temporal oscillations might be explained by some surface erosion caused by rain events. The %$CaCO_3$ was not investigated in depth to avoid destroying the slope during the first year after the treatment.

The ravines formed in the treated slope surface were mainly caused by the treatment fluids and rain occurring during the treatment (see Figure 3) and they remained stable once they were formed. This can be seen in the photographs taken in October 2022 and in July 2023 (Figure 6). The ravines in the bottom are in the untreated horizontal strip. It can also be seen that vegetation is starting to appear in the top of the slope.

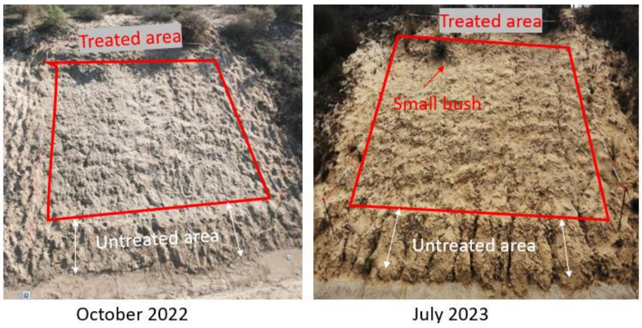

Figure 6. Photographs of the slope showing stable ravines in the treated area and the growth of a bush.

In general, the percentages of calcium carbonate measured were larger than the predicted value of 4%, as it can be seen in Figure 7, presenting its evolution along the horizontal alignment C in the middle of the treated area. The fact that the values are stable for the observed period suggests that the treatment is durable. Due to the dispersion of the results (Figs. 5 and 7) there is no obvious distinction between the zones where the two different treatment methodologies were used.

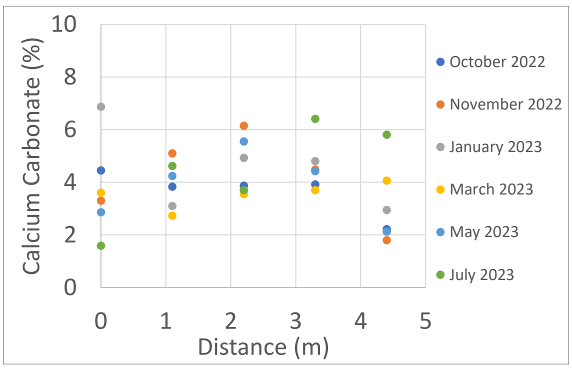

Figure 7. Values measured in horizontal alignment C.

Finally the presence of hard aggregates with high %$CaCO_3$ is another evidence of the heterogenity.

4 CONCLUSIONS

The photographs of the slope surface during the monitoring period confirm the presence of ravines caused by water. This extreme form of surface erosion started during the treatment, appearing to become stable along the monitoring time. The values of the percentage of calcium carbonate measured in the different zones of the treated area presented some oscillation along the monitoring time, which was explained by some erosion caused by rain. Nevertheless, they were larger than the target value of 4% and remained stable, which indicates that the amount of biocement is stable, and therefore the treatment is being durable. The slope will be under observation for a longer period to understand better the durability of the treatment.

The results are inconclusive in what it concerns if the treatment by injection and irrigation can be more effective than just by irrigation. The ongoing investigation of the distribution of calcium carbonate in depth is fundamental to better evaluate each methodology.

Finally, the growth of a small bush in the top of the slope suggests that vegetation can grow in the presence of the biocement. This will also be confirmed with further observation of the slope.

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