SYNTHESIS OF RESEARCH ON BIOGROUT SOIL IMPROVEMENT METHOD

Zsolt KALTENBACHER [1], Mátyás István MÁTÉ [2], Ludovic KOPENETZ [3], Vasile FĂRCAŞ [4], Iulia Consuela MOLNAR 5

[1] *PhD Stud. Eng., Technical University of Cluj-Napoca, Faculty of Civil Engineering, Geotechnics Department, kaltenbacher.zsolt@gmail.com*

[2] *PhD Stud. Eng., Technical University of Cluj-Napoca, Faculty of Civil Engineering, Geotechnics Department, kaltenbacher.zsolt@gmail.com*

[3] *PhD Stud. Eng., Technical University of Cluj-Napoca, Faculty of Civil Engineering, Structural Department, ludovic.kopenetz@mecon.utcluj.ro*

[4] *Lecturer Eng., Technical University of Cluj-Napoca, Faculty of Civil Engineering, Geotechnics Department, vasile.farcas@dst.utcluj.ro*

[5] *PhD, Assist. Eng., Technical University of Cluj-Napoca, Faculty of Civil Engineering, Geotechnics Department, iulia.molnar@dst.utcluj.com*

ABSTRACT

Because of the great rhythm of city developments, there is a great need for a new cost effective method for ground improvement. In this paper, a few chemical improvement technologies and a new biological ground improvement method called *Biogrout* are discussed. The method, used in the paper for a Sarmatian sand in Transylvania (Feleac locality) implies using microorganisms as catalysts in order to induce a microbial carbonate precipitation (MICP) to increase the strength and stiffness of cohesionless soils. For this calcium based procedure, the bacteria *Sporosarcina Pasteurii* (DSMZ 33) is used, while for the treatment solution urea ($CO(NH_2)_2$) and calcium chloride ($CaCl_2$) are used. The study presents the triaxial testing of sand probes treated with Biogrout and the comparison of results obtained with untreated sand probes.

Keywords: Microbial Induced Carbonate Precipitation (MICP); Biogrout; Sporosarcina Pasteurii

REZUMAT

Datorită ritmului mare de dezvoltare al oraşelor, importanta îmbunătățirii terenurilor de fundare arată o creştere intensă de interes în ultimii ani. Acest articol enumeră câteva metode chimice de îmbunătățire a terenurilor nisipoase şi descrie metoda *Biogrout*, care se bazează pe fenomenul numit *Microbial Induced Carbonate Precipitation* (MICP), utilizată pe un nisip sarmațian din Transilvania (Comuna Feleac). Metoda Biogrout consta in injectarea în teren a unor mase microbiologice şi a unor soluții chimice, cu ajutorul cărora se formează o legătura cristalizată rigidă între particulele nisipului. In experimentul descris de acest articol s-a folosit metoda *Biogrout* pe baza de calciu, unde rezultatul final al lanțului de reacții chimice este carbonatul de calciu, care va realiza legătura intre particulele de nisip. Pentru pornirea acestui lanț de reacții chimice este necesara prezența unui catalizator, care în cazul studiat este bacteria ureolitică *Sporosarcina Pasteurii* (DSMZ 33).

Cuvinte cheie: Microbial Induced Carbonat Precipitation (MICP); Biogrout; Sporosarcina Pasteurii

1. INTRODUCTION

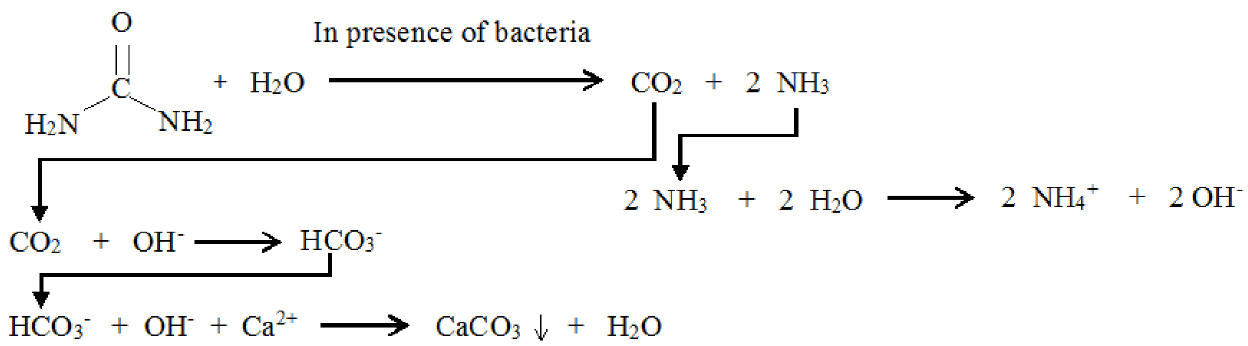
The development rhythm of cities in surface and vertically is in a continuous increase. The majority of cities are positioned near a river or a sea, which from the geotechnical point of view means poor foundation soils. Considering these facts, it is clear that ground improvement gains more and more importance for construction engineers. These ground improvement methods not only have to be efficient but also they have to be cost effective and environment friendly. From the procedural point of view, these methods can be mechanical or chemical-electrical.

Sandy soil improvement by mechanical methods rely on the change of the ratios between soils components (solid, void and water). This category of soil improvement is diverse, including surface and deep compaction; however they are expensive and high energy consuming. The other category of soil improvement involves the use of chemical solutions like cement, bitumen, sodium silicate etc.; however, the manufacturing of these materials also consumes a lot of energy. This study presents a new experimental soil improvement method in geotechnical engineering called Biogrouting, based on a chemical reaction process named *Microbial Induced Carbonate Precipitation* (MICP), catalyzed by an ureolytic bacteria.

Calcium based MICP is a reaction process where microbial activity results in carbonate precipitation in calcium saturated environments (Castanier et al., 1999). Precipitation of calcium carbonate, $CaCO_3$, is moderated by four key parameters: concentration of calcium and carbonate, pH of the medium and the availability of reaction cores. The precipitation of carbonates could be the outcome of different microbial processes; however, the most often-studied MICP is the hydrolysis of urea by the urease enzymes within a calcium-rich environment.

Previous studies have shown that *Sporosarcina Pasteurii* (DSMZ 33, formerly called *Bacillus Pasteurii*) is the most optimal catalyzing bacteria for MICP, because it has the greatest ureolytic activity and is not pathogenic (Fujita 2000, Mobley 1995). Sporosarcina Pasteurii is an aerobic bacteria cultivated in aerobic conditions.

Since the bacteria is chemoheterotrophic, which starts the chain reaction, uses urea as a source of energy through hydrolysis, after which the results are CO_2 and NH_3:



The hydrolysis of urea does not occur without the presence of the bacteria, which contains the urea enzyme (Sporosarcina Pasteurii). After the presented chain of reactions, a bonding material is formed between and on the sand particles. This bonding material is the calcium carbonate $CaCO_3$, where the source of calcium Ca^{2+} is the calcium chloride. The secondary result of the chain reaction is ammonium chloride, NH_4Cl:

$$2\ NH_4^+ + 2\ Cl^- \longrightarrow 2\ NH_4Cl$$

Considering that in Transylvania there are several kinds of sandy soils, Biogrout can be a viable ground consolidation or slope stabilization method in the future.

2. EXPERIMENTAL PART

The purpose of the experiments was to create triaxial probes from sand treated with Biogrout and to test these probes in the triaxial machine under confined drained conditions; the obtained results were compared with the results of experiments carried out by Dr. Iulia Consuela Molnar on the same untreated sand.

The triaxial test is a destructive method in geotechnical engineering, which gives the shear strength parameters of a soil probe (50 × 100 mm), by simulating almost perfectly the underground stress conditions.

The materials used for the experiment were: sand from Feleac locality, bacteria (from the ureolytic category: Sporosarcina pasteurii

DSMZ 33), $CO(NH_2)_2$ (urea), $CaCl_2$ (calcium chloride), H_2O (plain water). An important aspect is that special materials are not necessary for the method to work.

Urea is a fertilizer commonly used in agriculture; in fact, it is the diamide of the carbonate acid. It is a white grain material with a specific weight at T=20°C of 0.72-0.77 t/m³, being soluble in water.

Calcium chloride is a salt of calcite with hydrochloric acid $CaCl_2$; it is often successfully used as antiskid. The liquid used for bacterial multiplication and the injections is distilled water with a purity of 99.98%.

The sand probes treated with Biogrout were collected near Feleac locality. The sand is a fine micaceous material with gravel and silt components. As the predominant element in the sand is quartz, this can be qualified as a polymineral quartz sand.

For the microorganisms, it was necessary to prepare a culture medium and a growth medium. The culture medium is a solution named by DSMZ as Medium 220, which, according to this organization, contains the following ingredients: 20 g peptone, 5 g NaCl, 15 g agar and 1000 ml of tap water. The growth medium is similar with the culture medium, the only differences being that there is no agar in it and that it contains 20 g/L yeast extract, which proves to have a positive effect on growth, as shown by Whiffin (2007).

Before the injection of the bacterial solution into the triaxial probes, a few preparations are needed, i.e. dissolving $CaCl_2$ and $CO(NH_2)_2$ in water and drying the sand. The dissolution of $CaCl_2$ in water is an exothermic reaction, which, depending on the H_2O-$CaCl_2$ proportion, can result in temperatures of 50-60°C. It is possible that these high temperatures affect negatively the bacteria, so that it is advised to wait until the solutions cool down.

For the treatment solution, concentrations of 90 g/L of urea and 166.5 g/L of $CaCl_2$ (1.5 M equimolar) were used, which were injected three times for each probe, with intervals of 24 hours. For the second set, a fixation fluid of 0.05 mol $CaCl^2$ L^{-1} was applied directly after injecting the bacterial suspension, in order to enhance microorganism fixation, according to Harkes et al. (2010). The sand used for the study was gathered from a two-meter deep pit near the locality of Feleacu and was dried for four hours at 106°C before the experiments.

The triaxial probes were constructed in four steps (layers). After introducing a layer of sand in the cylinder forms, the bacterial solution was injected with a volume approximately half of the pore volume (10 ml/layer), then the fixation fluid was injected with the same volume. These operations were repeated and used for every probe. After two hours, these saturated probes were injected with the treatment solution. The treatment solution was injected again two times within an interval of 24 hours.

For obtaining the sand probes shear strength parameters, a total of three triaxial consolidated-drained (C-D) compression tests were performed. The results for the untreated simple sand were taken, for comparison purposes, from the PhD Thesis of Molnar (2012). The same relative density of I_D = 60% (289 g/probe) tested by Molnar was used in order to achieve credible and comparable results.

The triaxial test has three steps. The first step is saturation, which has two stages with identical σ_3' values. In the first stage, the pressure in the triaxial cell is σ_3=50 kPa and the back pressure (pore pressure) is u_b=30 kPa:

$$\sigma_3' = \sigma_3 - u_b = 50 \text{ kPa} - 30 \text{ kPa} = 20 \text{ kPa}$$

In the second stage, the cell pressure is σ_3 =100 kPa and the back pressure is u_b = 80 kPa.

$$\sigma_3' = \sigma_3 - u_b = 100 \text{ kPa} - 80 \text{ kPa} = 20 \text{ kPa}$$

When the saturation of the probes is complete, the consolidation stage is reached. In order to draw the Mohr-Coulomb circles, different values for σ_3' have to be taken and three probes have to be tested. The following values were used:

- Probe 1: σ_3 = 200 kPa and u_b = 100 kPa:

$$\sigma_3' = \sigma_3 - u_b = 200 \text{ kPa} - 100 \text{ kPa} = 100 \text{ kPa}$$

- Probe 2: σ_3 = 300 kPa and u_b =100 kPa

$\sigma_3' = \sigma_3 - u_b$ = 300 kPa - 100 kPa = 200 kPa

• Probe 3: σ_3 = 500 kPa and u_b = 100 kPa

$\sigma_3' = \sigma_3 - u_b$ = 500 kPa-100 kPa=400 kPa

The last step of the triaxial test is the failure stage, which was conducted with a 0.1 mm/min press speed, until a 20 mm settlement was reached for each probe.

3. RESULTS

The results from the triaxial tests were analyzed with two different methods. The first was the Mohr-Coulomb method, which presumes the construction of Mohr's circle from the available data and the drawing of the line of Coulomb to obtain the shear strength parameters in a (σ, τ) coordinate system, using the effective efforts σ_{1I} and σ_{3I} calculated at the end of each test from data provided by the device (see Fig. 1). The second method was the critical state method, which showed results similar to the first one.

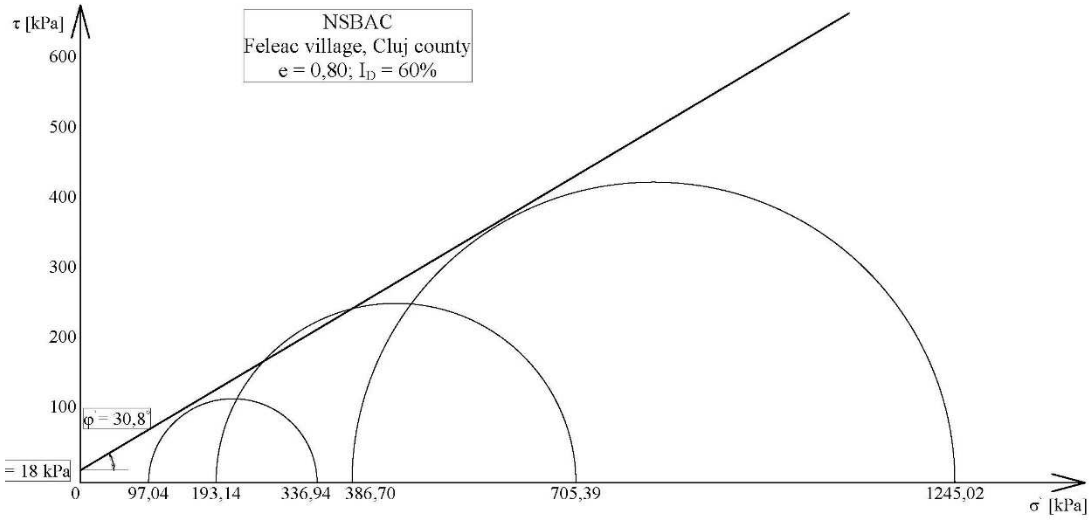


Fig. 1. Mohr-Coulomb method - results for the Biogrout treated sand

The results do not show a significant increase of the internal friction angle; however, they show an increase of the cohesion up to a value of 18 kPa. The use of the fixation fluid mentioned earlier proved to be a success. The increased value of cohesion indicates the cohesion-like cementation of the Biogrout treated probes.

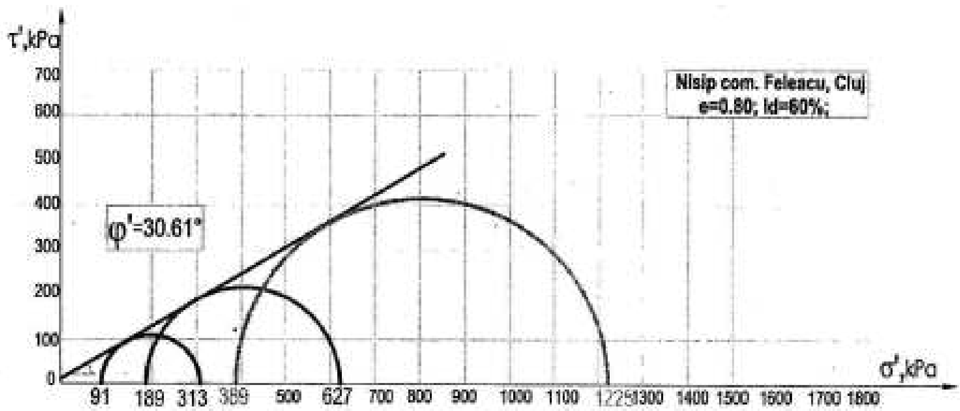


Fig. 2. Mohr-Coulomb for the untreated sand (adapted from Molnar, 2012)

The second method used for the analysis of results is the Critical State Line method, which presumes the construction of a critical state line in a (p^l, q^l) coordinate system on the basis of effective efforts σ_{11} and σ_{31}, calculated at the end of the triaxial tests. The results show a slight increase of cohesion (19.27 kPa) and almost the same internal friction angle (30.29°).

While conducting the compression tests, higher axial efforts and lower settlements were observed for the Biogrout treated probes, in comparison with the data from the untreated sand in the same time frames, which indicates a certain cementation and increase of modulus of elasticity. The effort-settlement diagram for the probes and for σ_3 was constructed and compared with the same diagram of the untreated sand probes: (i) (blue) NSF - untreated sand from Feleacu, Cluj; (ii) (green) NSBAC- Biogrout treated sand from Feleacu, Cluj (Fig. 3).

On the σ - ε diagram for σ_3 = 200 kPa in Figure 3, the difference between treated and untreated probes can be seen most clearly: the treated probe tends to deform in compression with the same rate for the first 5 mm; however, the treated probe shows a steeper stress - deviation line, which may indicate a uniform cementation of the treated probes.

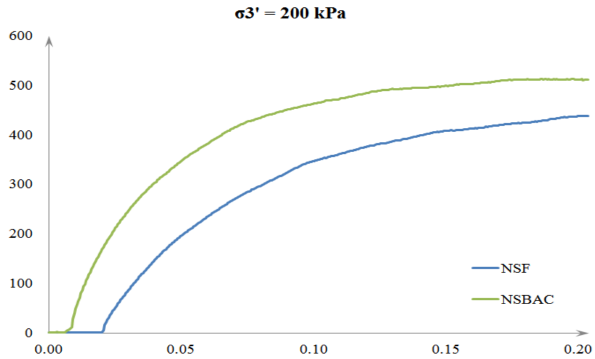


Fig. 3. σ - ε diagram for σ_3' = 200 kPa

The diagram shows significant increase of the modules of elasticity E_i, E_{50}, E_f for the treated probes, in comparison with the untreated sand; results are presented in Table 1.

Table 1. *Shear strength parameters and modulus values for treated and untreated probes*

Specimen type	Angle of internal friction □` (°)	Modulus of elasticity initial E_i (mPa)	Modulus of elasticity 50% E_{50} (mPa)	Modulus of elasticity final E_f (mPa)	Lateral pressure containment σ_3' (kPa)	Cohesion c (kPa)
NSF	30.61	24.5	12.8	5.36	100	0
NSBAC	30.80	45.86	17.04	4.73	100	18
NSF	30.61	19.71	16.67	4.62	200	0
NSBAC	30.80	37.32	27.23	5.05	200	18
NSF	30.61	27.47	29	6.13	400	0
NSBAC	30.80	27.49	25.43	5.66	400	18

There is a 40-90% increase of E_i and a 40-60% increase of E_{50} for the first two confinement values (100 and 200 kPa); however, for a 400 kPa value of the confinement stress there is a 10% decrease of E_i and E_{50} for the treated probes. The values of E_f vary inconsistently around the value for the untreated sand.

From the triaxial results, it is also important to note that the consolidation time was 50% less for σ_3 = 200 kPa, almost the same for σ_3 = 300 kPa and 30% less for σ_3 = 500 kPa, which can also indicate the cementation of the Biogrout treated probes.

4. CONCLUSIONS

The obtained results from the Biogrout treated probes were compared with data from the same type of untreated sand. The analysis showed significant positive differences between Biogrout treated and untreated probes, which concludes the success of the experiment. After analyzing all the available data, the following conclusions can be drawn.

- All the Biogrout treated probes reached a higher critical effort than the untreated sand probes and all of the treated probes showed an increase of the module of elasticity, which indicate a successful cementation process and increase of the sand body stiffness.
- Obtaining a cohesion of 18 kPa by the Mohr-Coulomb method confirms the theory that, by the Biogrout process, $CaCO_3$ crystals are formed at the contacts of sand grains realizing a cohesion-like bond between them.
- The unchanged values obtained for the internal friction angles of the treated probes indicate that the low amount of nutrients injected as treatment solutions was not enough to significantly change the sand macro-structure, but only capable of forming a bond-like cohesion between sand grains. Probably better results can be achieved by the optimization of the injection process and by microbial screening, or by increasing the number of treatment solutions injected. The possible increase of the internal friction angle by increasing the number or the concentration of treatments remains to be studied in the future.
- All the treated sand probes showed smaller deformations then the untreated ones for the same compression efforts (increase of the modulus of elasticity by 40-90%) which indicates that, in the future, Biogrout would be ideal for improving sandy soils with suspicions of intensive settlement.
- The great advantage of Biogrout would be the elimination of the use of traditional materials, which contain high-embodied energy, rely heavily on limited natural resources and are highly CO_2 pollutants. The main components of Biogrout would be $CO(NH_2)_2$ (urea), $CaCl_2$ (calcium chloride), H_2O (water) and ureolytic bacteria, all these being environment-friendly and low-cost materials.
- The disadvantage of Biogrout would be the production of NH_4Cl as a secondary effect of MICP, which is not environment-friendly and needs to be eliminated from the treated soil. Former studies proposed washing out this product with water; however, we believe that by the injection of nitrifying bacteria this problem can be solved. This direction remains to be studied in the future.

The final conclusion is that the experiment proved the viability of Biogrout in laboratory conditions and the obtained results offer a strong base for further research.

5. ACKNOWLEDGEMENT

The authors would like to acknowledge the support of Vasile Farcas and Iulia Molnar, from the Geotechnical Department of the Technical University of Cluj-Napoca. The authors are grateful for the microbial preparation to Vasile Muntean, from the Microbiology Department of Babes-Bolyai University Cluj-Napoca.

6. REFERENCES

1. Castanier, S., Le Metayer-Levrel, G. & Perthuisot, J.-P. *Ca-carbonates precipitation and limestone genesis - the microbiogeologist point of view*. Sediment Geol 126, p. 1-4, 9, 1999.
2. Chu, J. *Biogrout & other grouting methods*. Proc. ISSMGE - TC 211 InternationalSymposium on Ground Improvement IS-GI, 31 May & 1 June 2012, Brussels, Belgium, p. 1-9, 2012.
3. De Jong, J.T., Fritzges, M.B. & Nusslein, K. *Microbially Induced Cementation to Control Sand Response to Undrained Shear*. ASCE Journal of Geotehnical and Geoenviromental Engineering vol. 132, p. 1381-1392, 2006.
4. Ivanov, V., Chu, J. *Applications of microorganisms to geotechnical engineering for bioclogging and biocementation of soil in situ*. Reviews in Environmental Science and Biotechnology vol. 7, p. 139-153, 2008.
5. Farcas, V., Molnar I.C., Mate M.I., Kaltenbacher Zs., Kopenetz L. *Study of sand behavior improvement using biogrouting*. XV Danube-European Conference on Geotechnical Engineering, Vienna, Austria, 9-11 September 2014.
6. Fujita, Y., Ferris, F.G., Lawson, R.D., Colwell F.S. & Smith, R.W. *Calcium carbonate precipitation by ureolytic subsurface bacteria*. Geomicrobiology Journal vol. 17, p. 305-318, 2000.
7. Harkes, M.P., Booster, J.L., van Paassen, L.A., van Loosdrecht, M.C.M. & Whiffin, V.S. *Microbial induced carbonate precipitation as ground*

improvement method – bacterial fixation and empirical correlation CaCO3 vs. strength. Proc. International conference on BioGeoCivil Engineering, Delft, Netherlands, p. 23-25, 2008.
8. Harkes, M.P., Van Paassen, L.A., Booster, J.L., Whiffin, V.S. & Van Loosdrecht, M.C.M. *Fixation and distribution of bacterial activity in sand to induce carbonate precipitation for ground reinforcement*. Ecol. Eng. vol. 36(2), p. 112-117, 2010.
9. Molnar, I.C. *Contributii privind influenta modelelor de calcul in probleme de inginerie geotehnica*. PhD thesis, Technical University of Cluj Napoca, 2012.
10. Van Paassen, L.A., Ghose, R., Van der Linden, T.J.M., Van der Star, W.R.L. & Van Loosdrecht, M.C.M. *Quantifying Biomediated Ground Improvement by Ureolysis: Large Scale Biogrout Experiment.* Journal of Geotehnical and Geoeviromental Engineering vol. 136, p. 1721-1728, 2010.
11. Whiffin, V.S. *Microbial CaCO3 Precipitation for the production of Biocement*. PhD. thesis, Murdoch University Western Australia, 2004.
12. Whiffin, V.S., Van Paassen, L.A. & Harkes, P.M. *Microbial Carbonate Precipitation as a soil improvement tehnique.* Geomicrobiology Journal vol. 24, p. 417-423, 2007.