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# Iron-Based Bio-Grout For Soil Improvement and Land Reclamation

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## ABSTRACT

Chemical grouts have often been used in geotechnical applications. However, they are expensive, usually toxic, and may be harmful to the environment. A new type of grout, biogrout, which is based on ferrous/ferric salts, has been developed using microbial technology. The time for the biogrout to take effect and the extent that biogrouts penetrate the soil depend on the concentration and activity of specific bacteria in the biogrout. The reaction time varies from several minutes to several days. Testing results show that ferrous/ferric-based biogrouts are applicable for construction of reservoirs, ponds, dams, and land reclamation. The biogrout also increases the strength and decreases the permeability of the soil. Geotechnical applications of the biogrout could be; 1) formation of grout curtains; 2) diminishing piping of earth dams and dikes; 3) construction of reservoirs and ponds; 4) seepage control; 5) fixation of the leakages of ground water in underground constructions; 6) reduction of pipeline corrosion; 7) land reclamation; 8) sealing of tunnel seepage; 9) the reduction of soil liquefaction.

## INTRODUCTION

Chemical grouting is a common technique adopted in geotechnical engineering to improve the mechanical properties of soil (Karol, 2003). In adopting this method, grout is injected into the voids of soil to increase the strength or reduce the permeability of soil. However, chemical grouting can be expensive and toxic for environment.

An alternative approach is to use biogrout (Ianov and Chu, 2008; Mitchell and Santamarina, 2005). Biogrouting is to fill the voids, channels or fissions in soil or rock through microbial activity or by the microbial products. Due to small size of bacterial cells, 1-3 µm, biogrouts can be applied to soils with permeability below $10^{-6}$ m/s. It can decrease the permeability to $10^{-10}$ m/s. This effect is similar to the effect of chemical grouts (Sarsby, 2000; Indraratna and Chu, 2005). However, cement grout is applicable for soils with permeability below $10^{-4}$ m/s and can decrease permeability up to $10^{-6}$ m/s (Sarsby, 2000).

The use of microbial technology into geotechnica engineering has been called Microbial geotechnology. It is a branch of geotechnical engineering aiming to improve the mechanical properties of soil so that it will be more suitable for construction and environmental purposes (Ivanov and Chu, 2008). There are several mechanisms that are suitable for biogrouting into soil or rock: 1) filling of the voids and channels in soil with inorganic compounds settled due to activity of microorganisms; 2) filling in the pores and channels with microbial biomass and polysaccharides; 3) cementation (binding) of the particles with inorganic compounds, which is mediated by microorganisms; 4) biocementation (binding) of the particles with microbial biomass and polysaccharides; 5) formation of salt bridges between the soil particles and colloids mediated by microorganisms; 6) microbial formation of gas bubbles and desaturation of soil for prevention of liquefaction.

The major advantages of biogrouts over chemical grouts are lower cost and low or even zero harmful effects on urban environment (Ivanov and Chu, 2008). However, application of the biogrout is more complicated than chemical grout because biogrout includes both microbial and chemical components and its geotechnical application is site-specific. An advantage of biogrout in comparison with the conventional cement is that the solution of biogrout has low viscosity and can penetrate into the porous soil by gravity.

Potential geotechnical applications of the biogrouts are as follows: 1) to form grout curtains to reduce the migration of pollutants after accidental spill or leakage of toxic pollutant into permeable soil; 2) to prevent piping and to enhance stability of earth dams and dikes; 3) to construct the reservoirs and ponds; 4) seepage control; 5) to control erosion of the banks or coastal area; 6) to increase slope and excavation stability; 7) to reduce the liquefaction potential of soil; 8) to enhance the stability of dams; 9) to increase the bearing capacity of foundations; 10) to fix leakages of ground water in underground constructions; 11) soil settlement control; 12) decrease soil expansion potential; and 13) reduce corrosion of the pipelines.

Geotechnical applications of biogrouts that are relevant to the construction of megacities include land reclamation, stabilization of the roads and pipelines, the sealing of the drippings in the tunnels, and the reduction of the liquefaction potential of soil. One aim of our research was to develop biogrout that is suitable for urban geotechnical applications.

## EXPERIMENTAL INVESTIGATION

### Settling of biogrouts

The following biogrouts have been tested to strengthen soil and to decrease permeability of the sandy soil: 1) conventional biogrout containing calcium chloride, urea, and urease-producing bacteria. The conventional biogrout has been used as control; and 2) iron-based biogrout, which was ferrous/ferric-containing solution produced by iron-reducing bacteria from iron ore and organic waste, with an addition of urea and urease-producing bacteria to increase pH.

The major chemical reactions in conventional biogrout are as follows:

$$(NH_2)_2CO + 3H_2O \rightarrow CO_2 + 2NH_4^+ + 2OH^- \qquad (1)$$

which is performed by urease-producing bacteria, and

$Ca^{2+} + CO_2 + 2\,OH^- \rightarrow CaCO_3\downarrow + H_2O$ (2).

The major chemical reactions in innovative biogrout are as follows:

$1.5\,(NH_2)_2CO + 4.5H_2O \rightarrow 1.5CO_2 + 3NH_4^+ + 3OH^-$ (3),

which is performed by urease-producing bacteria, and

$(HCOO)_3\,Fe + 3OH^- + 3NH_4^+ \rightarrow Fe(OH)_3\downarrow + 3\,HCOONH_4$ (4).

Production of hydroxide ions can be performed also by denitrifying bacteria using organic substances as electron donor:

$NO_3^- + 2.5\,CH_2O \rightarrow N_2 + 2.5CO_2 + 1.5H_2O + 2OH^-$ (5),

or sulphate-reducing bacteria:

$SO_4^{2-} + 2CH_2O \rightarrow H_2S + 2CO_2 + 2\,OH^-$ (6)

Typical pH that can be created by these processes is from 8.3 to 9.5.

Ferric formate and lactate but not ferric citrate are suitable for the precipitation at pH above 8.5 (Fig. 1). It means that ferric salts of organic acids produced by fermenting bacteria are suitable as the components of biogrouting mixture.

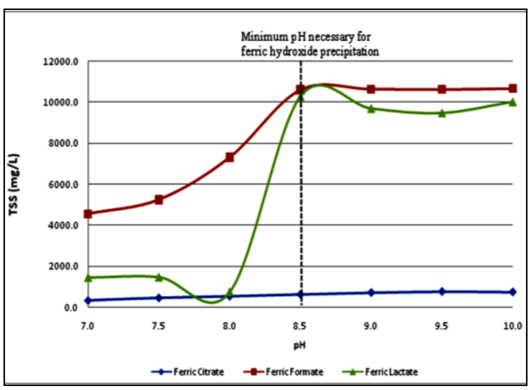


Fig.2. Precipitation of ferric hydroxide (TSS) depending on pH in the biogrouting process.

Depending on activity of urease-producing bacteria or urease the rate of precipitation could be faster. For example, calcium-based grout can form precipitate after 10 minutes.

## Sandy soil treated with biogrouts

Constant head permeability tests in a triaxial cell and unconsolidated undrained triaxial tests were carried out to measure the change in the soil properties of the treated soil. The geotechnical parameters of microbial soil biocementation depend on the mass ratio of biogrout and soil particles as well as a number of the treatments in the series of the repeating treatment, see Figs. 2 and 3.

The compressive strength for the air dried samples increased gradually with the number of the treatments using iron-based biogrout and were in the range from 11 kPa to 18 kPa. Whereas, the compressive strength increased from 19 kPa to 56 kPa just for two treatments of the oven dried samples, to 79 kPa, 106 kPa and 149 kPa after the 3$^{rd}$, 4$^{th}$ and 5$^{th}$ treatment, respectively (Fig. 2). The permeability of the soil was reduced from $1.1 \times 10^{-4}$ m/s for untreated sample to $5.9 \times 10^{-5}$ m/s for sand sample after 5 treatments (Fig. 3).

Conventional microbial grout based on calcium salt has decreased the permeability of sandy soil up to $2.5 \times 10^{-9}$ m/s and increased the unconfined compressive strength (UCS) for dry samples to 1600 kPa. For the wet samples, the maximum UCS was 800 kPa (Fig. 4).

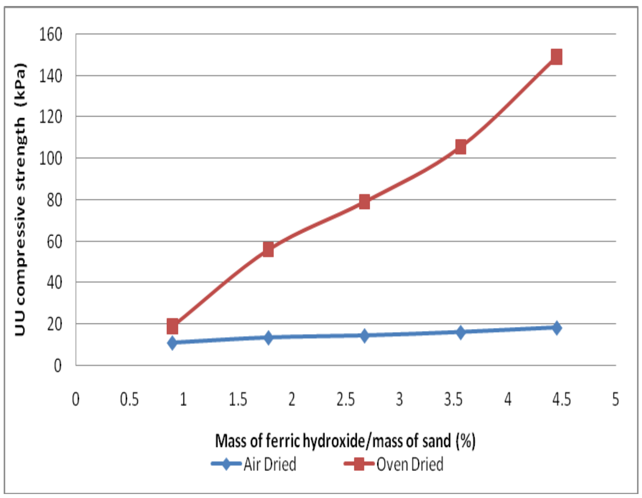


Fig. 2. The unconsolidated undrained (UU) compressive strength triaxial test results of both the oven dried and air dried sand samples biotreated using iron-based grout. Points show the values in the sequence from 1 to 5 treatments of the sample.

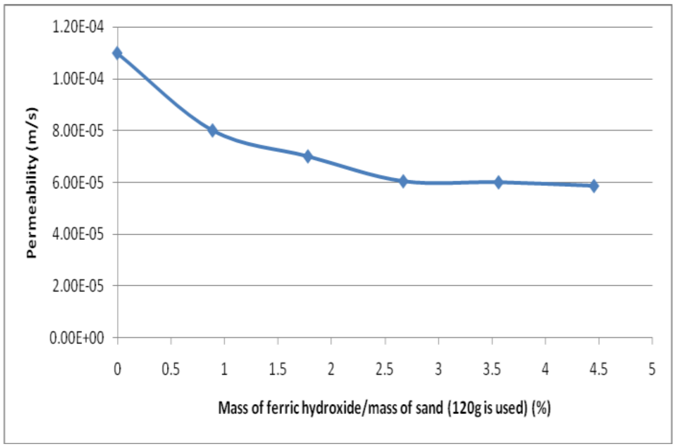


Fig. 3. Permeability of biocemented sand samples.

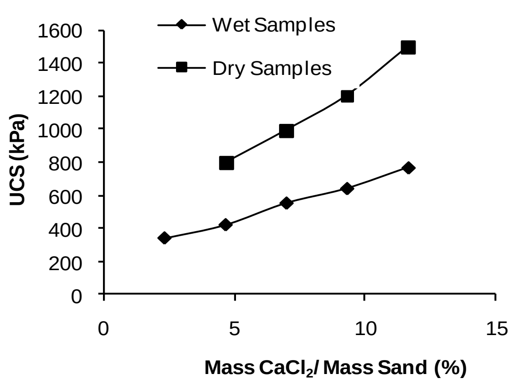


Fig. 4.The uncomfined compressive strength (UCS) results of both the wet and air dried sand samples biotreated using calcium-basd biogrout.

## Mechanisms of biogrouting

The scanning electron micrograph (SEM) of untreated and biotreated sand samples are shown in Figs. 5 a-c. A comparison shows that the sand particles are bond together after treatment with iron-based biogrout and by calcium-based biogrout. It can also been seen that the pores are also filled by biogrout. This explains the mechanisms of biogrout.

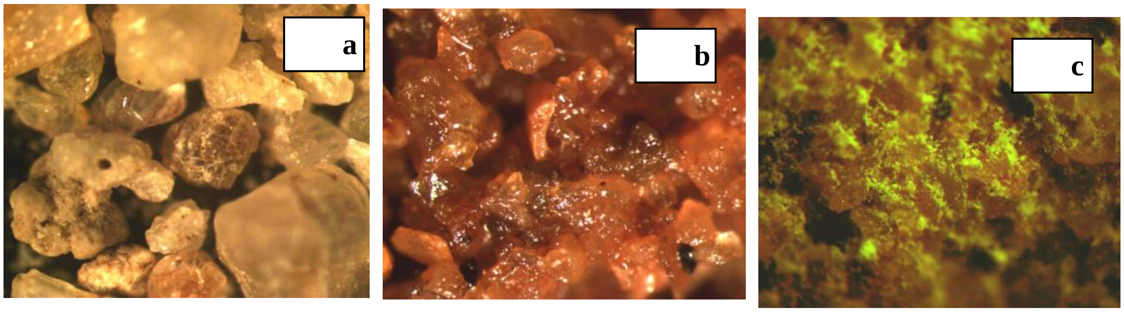


Fig. 5 a-c. Micrographs of untreated and biotreated sand samples.
(a) untreated sand; (b) sand treated with the iron-based biogrout; (c) sand treated with the calcium-based biogrout.

## CONCLUSIONS

Because of lower cost of iron-based grout and not significant increase of strength of wet samples, the potential geotechnical applications of the iron-based biogrouts include large-scale reduction of permeability, which is not required significant increase of mechanical strength of soil. These urban geotechnical applications could be as follows: 1) to form grout curtains to reduce the migration of pollutants after accidental spill or leakage of toxic pollutant into permeable soil; 2) to diminish piping of earth dams and dikes; 3) to construct the reservoirs and ponds; 4) seepage control; 5) to fix leakages of ground water in underground constructions; 6) reduce corrosion of the pipelines; 7) land reclamation; 8) the sealing of the drippings in the tunnels; 9) the reduction of the liquefaction potential of soil.

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