

# An investigation of soft soil electrokinetic biocementation

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**ABSTRACT:** Nature-based and nature compatible techniques are increasingly gaining the interest of geotechnical engineers, in the drive towards net carbon zero and enhanced sustainability of geotechnical engineering practices for the provision and maintenance of infrastructure. This contribution presents results of a collaborative work between academia and industry, towards the setting up of a field pilot of biocementation (the biomimetic production of natural cementing agents) for the improvement of soft foundation soils of historic railway embankments in East England. The aspects described are laboratory biostimulation-biocementation tests, in which treatments are supplied electrokinetically as a means of treatment implementation under existing infrastructure, and preliminary modelling to instruct on suitable setups for the field trial and to assess the environmental sustainability of the solutions (Life Cycle Assessment, LCA). The results shown in the paper indicate 4-10 times increase in the undrained shear strength of the soft organic soils and attest substantial amounts of carbonate precipitation, while preliminary LCA indicates an overall improved sustainability compared to electrokinetics with cement or lime slurries.

**KEYWORDS:** Ground improvement, biocementation, electrokinetics, soft soil, organic soil.

## 1 INTRODUCTION

Current government strategies worldwide, require infrastructure to be provided in an economical and environmentally responsible manner, reducing material use, embedded carbon and other impacts on the natural environment and ecosystems. Thus, it is becoming critically important in engineering practice to develop innovative, cost-effective, and overall, more sustainable ground improvement techniques allowing to mitigate natural and man-made hazards, while minimising waste and other environmental impact. In line with this, biocementation, a technique using microorganisms to induce precipitation of minerals and thus improve the engineering properties of the soil, has recently emerged as a promising ground improvement technique towards this goal. This is because it is based on a natural process, and the treatments are potentially renewable and more cost-effective if the long-term costs are considered (Safdar et al, 2021a).

The technique has recently attracted the interest of Network Rail, owners and operators of the largest part of the railway network in England, Scotland and Wales. They commissioned Ramboll UK and London South Bank University to undertake research on the feasibility of biocementing problematic soft soils of the network, taking a site in East Anglia as a case study, for potential field pilot demonstration. At this site, there are maintenance problems owing to underlying soft soils with mechanisms of track deterioration as a combination of settlement due to dewatering in the surround farmland area, the compaction of the underlying soft ground, outwards movement of the soft ground due to the loading of the embankment, seasonal shrinkage, and peat wastage caused by oxidation (Safdar et al, 2022). British Geological Society (BGS) maps (2024 a and b) show the geological setting of the site as follows: the bedrock is formed of the Oxford Clay Formation comprising SILT/CLAY. Locally, PEAT is shown to overlay this in places also at the surface over the site, with Marine Alluvium (Terrington Beds) further to the east and Older Marine/Estuarine SAND and GRAVEL (March gravels) to the west. There are other

Flandrian layers potentially present that consist of Alluvium. Existing records from historical logs confirm the presence of GRAVEL and soft CLAYS/SILTS in the area overlying PEAT. This overall geological setting was confirmed by investigatory boreholes and trial pits as part of this project. However, the ground investigation also revealed the high variability of the superficial deposits making the characterisation of the site with a single site-wide idealised layering profile problematic. For example, in some cases, there are multiple PEAT bands but it is not clear that these bands join together across the site. There is often a layer of Medium or very dense SAND and/or GRAVEL laying atop the Oxford Clay Formation, overlain by Very Soft/Soft silty CLAY, however in some cases there is PEAT immediately on the Oxford Clay Formation and the SAND GRAVEL sits on top of, or within PEAT bands.

Considering this setting, it is obvious that biocementation is challenging, due to the high variability and the presence of fine and organic soils for which biocementation feasibility has not been firmly established. International literature on biocementation by Microbially Induced Carbonate Precipitation (MICP) is dealing by far mainly with coarse grained soils and not clays or soils of organic content, including organic clays and peats, as in the case of the trial site. For clays, biocementation feasibility is considered challenging due to narrow pore throat size. For organic soils and peats biocementation is challenging due to the high organic matter and the high water content. There is relatively little evidence on the biocementation of these soil types, including work by Boise University on clay biocementation (e.g. Islam et al, 2020; Chittoori et al, 2020) and London South Bank University demonstrating biocementation of clays (e.g. Mwandira et al, 2023 and 2024) and amorphous peat (Safdar et al 2021a,b and 2022). Additionally, a challenge is the implementation of the biocementation treatments in this highly variable setting with soft and organic soils under existing infrastructure, while ensuring treatment uniformity. Electrokinetics (EK), where an electric current is applied within the porous media to induce specific transport phenomena, has been identified as a possible

viable implementation solution. A study of EK biocementation feasibility has thus been commissioned by Network Rail.

This paper presents selected results of this project, towards the setting up of a field EK biocementation pilot in East Anglia. It focuses on mesocosm studies, assessing the feasibility of EK biocementation using biostimulation of indigenous microorganisms. The targeted metabolic pathway is that of the inter-conversion between CO<sub>2</sub> and the bicarbonate ion HCO<sub>3</sub><sup>-</sup> mediated by carbonic-anhydrase (CA) produced by heterotrophic bacteria. This pathway was chosen because, unlike the popular ureolytic pathway used by most researchers worldwide, it does not release undesirable ammonia by-products that need to be managed, making it more suitable for large scale applications; additionally, the CA pathway has the potential of CO<sub>2</sub> sequestration. Namely, in this process, CA utilises gaseous CO<sub>2</sub> to give hydrated aqueous CO<sub>2</sub>, which reacts with H<sub>2</sub>O forming H<sub>2</sub>CO<sub>3</sub>. The H<sub>2</sub>CO<sub>3</sub> ionises in water to generate HCO<sub>3</sub><sup>-</sup> and H<sup>+</sup>; the HCO<sub>3</sub><sup>-</sup> further ionises in the alkaline environment, producing CO<sub>3</sub><sup>2-</sup>. To form a biomineral, metal ions (e.g., Ca<sup>2+</sup>, Mg<sup>2+</sup> or Fe<sup>2+</sup>) are provided so that precipitates are formed from the reaction (Mwandira et al, 2024).

## 2 MATERIALS AND METHODS

### 2.1 Tested soils

For the laboratory tests we worked with bulk samples coming from 1.7m - 4m depth. The soft clay ranged from brown silty clay with no obvious plant remains and low organic content and black/grey clay of high organic content. In most cases they were classified as clays of high plasticity (CH) but one intermediate (CI), one silt of high plasticity (MH), one very high plasticity (CV) and one extremely high plasticity (CE) clay were also found. The two clays shown in this paper had the following characteristics respectively: LL= 63%, PL=33%, PI=30% (silty clay classified as MH) with moisture content of the bulk sample 48% and a low organic content (3.9%); and LL=85%, PL=54%, IP=31% (classified as CV) with moisture content of the bulk sample 57% and a high organic content (12.9%).

The peat soil we tested (pH=8) contained large pieces of wood; it had a variable content of organic clay; accordingly, the water content ranged from >520% to 100%, the latter being in samples of high organic clay content. X-Ray Diffraction (XRD) analysis of the peat showed that the mineral portion contained predominantly quartz, kaolinite and muscovite/illite. Following von Post's classification the peat was H4-H3 (slight-very slight decomposition), B2(500%-1000% water content)-B3 (<500% water content); F2 (moderate fine fibre content); C2 (moderate coarse fibre content); W2 (moderate wood content), N3 (60-80% organic content), A1 (slight smell); pH0 (neutral pH). However, there was considerable variability in the bulk sample.

### 2.2 Experimental procedures and setups

The investigation followed the usual steps starting from small laboratory scale microcosm (cylinders of 50mm diameter and 100mm height) to mesocosm/bench scale studies, with 1m<sup>3</sup> scale tests being ongoing. In all cases, soil from the bulk samples was compacted at its natural water content and dry densities determined based on window samples. Static compaction was used as it is known to be more efficient for fine grained soils. Tests were carried out in duplicate, as a minimum, unless stated otherwise.

Initial bench scale experiments used four types of EK cell prototype setups to compare differences in the treatment effectiveness, i.e., respectively: metal plates inside electrolyte chambers (Figure 1), metal plates inside soil, and setups with a well in the middle of the cell and electrodes either inside the electrolyte chambers or inside the soil at the soil compartment

edges. Later, bench scale setups considered more realistic field configurations (see section 4 below). Different electrode types were tried, including copper, graphite, steel and titanium.

Treatment periods of 2-4 weeks were used consistently with our previous studies. Biostimulation media (yeast 3-10 g/L; 0.08-0.1M NaHCO<sub>3</sub>; 0-5g/L peptone; 0-5g/L NaCl, C<sub>2</sub>H<sub>3</sub>NaO<sub>2</sub>; 0-1 μM ZnSO<sub>4</sub>) were injected first; after a week, biocementation solutions (NaHCO<sub>3</sub> and Ca(C<sub>2</sub>H<sub>3</sub>O<sub>2</sub>)<sub>2</sub>, ranging from 0.1M to 0.25M) were injected every 2 days, in 2 biocementation cycles. During testing, the pH was carefully monitored, so that it does not vary to levels that could affect the survival and activity of bacteria or cause carbonate dissolution. To avoid sharp pH changes electrode polarity reversal was used. EK tests were performed at voltage gradients of 0.4-0.5V/cm (see Safdar et al, 2021a,b). Regular voltage and current measurements were performed. At the end of treatment, cylindrical specimens of 100mm height and 50mm diameter were extracted from various locations in the cell for Unconfined Compressive Strength (UCS) testing; undrained shear strength *S<sub>u</sub>* was also determined from fall cone tests using Eq. 1 by Hansbo (1957), reported in Leroueil and Le Bihan (1996):

$$S_u = 9.8 * K * M / P^2 \quad (1)$$

where *M* is the mass of the cone reported in grams (80g for the standard BS cone used), *P* the cone penetration in mm and *K* a parameter depending on the angle of the cone. For an apex angle of 30° which is the angle of the British Standard penetration cone, typical *K* values are 0.8-1.

Moisture content, pH and carbonate content at the same locations were also measured. The latter measurements were based on acid consumption testing of oven-dried soil samples, washed using a 2M HCl solution (see Mwandira et al., 2023).

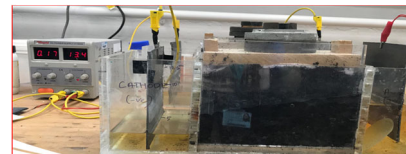


Figure 1. Electrokinetic cell setup used in the presented tests

## 3 INDICATIVE RESULTS

As in the available literature on biocementation of organic soils/peats undrained strength results are based on fall cone correlations, our *S<sub>u</sub>* results presented here will be based on this method for consistent comparisons. However, UCS results are also shown elsewhere (Mavroulidou et al, 2025). All presented results are from EK with graphite electrodes. Figure 2 shows indicative *S<sub>u</sub>* results for peat, achieving up to a sixfold increase compared to the untreated soil. There is a high increase in the carbonate content of the samples in all cases, with 7-13% new carbonate forming, confirming bioprecipitation, as do crystals, clearly seen in the treated samples (see Figure 3). Chen et al (2021) report similar fall cone test *S<sub>u</sub>* values for a peat of higher water content (711-824%) in which bamboo fibres were incorporated to decrease the water content. Oedometer tests (25-100 kPa effective stress) showed average values of coefficient of volume compressibility *m<sub>v</sub>*, decreasing 1.5 times (10.4 m<sup>2</sup>/MN vs 6.9 m<sup>2</sup>/MN for the untreated and treated peat respectively), and a two-fold increase of coefficient of consolidation *c<sub>v</sub>* after treatment (i.e. 0.26 m<sup>2</sup>/y vs 0.54 m<sup>2</sup>/y for untreated and treated peat respectively), indicating a small effect only in the average coefficient of permeability. Note that in the EK tests of the peat it was repeatedly observed that water (or biostimulation treatments) could readily flow through the peat simply being driven by the hydraulic gradient, without the need for an electric current. This was unexpected but it was

observed consistently in all EK samples, although prepared by six different researchers during the project. In the literature, the reported peat permeability coefficient (in our case, fibrous/pseudo-fibrous) can vary by 3 orders of magnitude but starting values of  $10^{-5}$  m/s order of magnitude are also mentioned (e.g., Mesri et al, 1997; Hobbs, 1986) which would be consistent with the observations of our bench scale tests. On the other hand, our falling head measurements found the permeability of the peat (in the vertical direction) to be in the order of  $10^{-6}$ - $10^{-7}$  m/s. However, the permeability is dependent on the applied load.

Figures 4-5 show indicative  $S_u$  results based on the clay sample with high (12.9%) and low organic content (3.9%) respectively. Treated soils achieved respectively  $S_u$  values of up to 73 kPa (i.e. 4.8 times higher than the untreated soil) with an increase in carbonate content of 6.7-8.6% compared to the untreated soil and  $S_u$  values of up to 107 kPa (a tenfold increase compared to the natural clay) and an average increase in carbonate/calcite content of 2% compared to the natural clay.

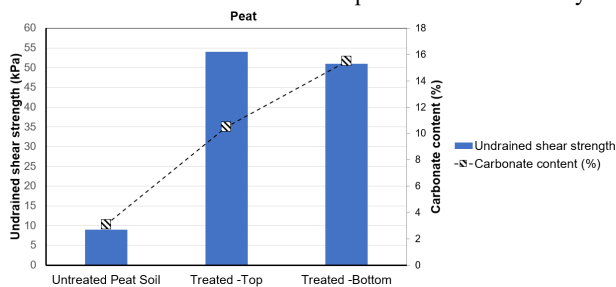


Figure 2. Indicative results for peat at top and bottom of samples

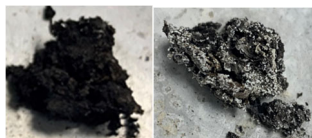


Figure 3. Peat photos before treatment (left) and after treatment (right)

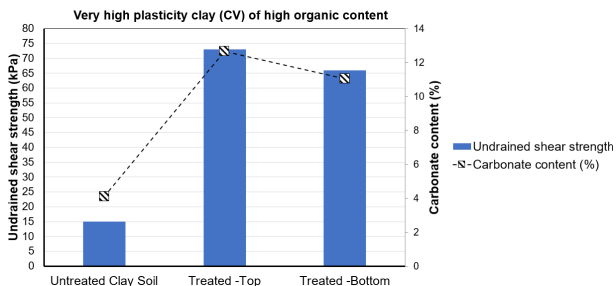


Figure 4. Undrained shear strength and carbonate content of biostimulated very high plasticity, high organic content clay

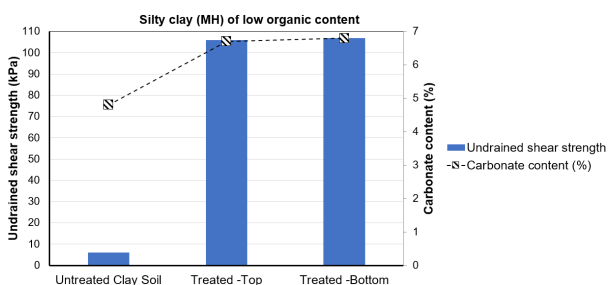


Figure 5. Undrained shear strength and carbonate content of biostimulated low organic content silty clay

## 4 CONSIDERATIONS FOR FIELD TESTING SETUP

### 4.1 Electrokinetic setup in the field

When transferring the technique to the field, electrodes will typically be placed in boreholes, which may be arranged in a number of configurations, including in parallel rows, square or

hexagonal arrangements, etc. In most geotechnical applications the aim of EK has been to dewater the soil by electroosmosis, and the number of anodes is often higher than that of cathodes. For example, in a hexagonal arrangement six anodes would surround a single cathode and in arrays of such arrangements, there would be twice as many anodes as cathodes, which does not suit well polarity reversal during treatment; additionally, the prevalence of anodes may lead to acidic pH to predominate (not suitable for calcite precipitation). Thus, we have considered arrangements based on rectangular grids with different schemes for assigning electrode polarity. Examples of such arrangements are shown in Figure 6: arrangements A and C are based on a square grid and in arrangement B the spacing between individual anodes or cathodes is half the spacing between the anode and cathode arrays. Arguments about symmetry of flow lead to the identification of the hatched areas in Figure 6 that we should examine to determine the distribution of potential (and hence lines of flow) in the ground between the electrodes. Figure 7 (a,b,c) show the finite element meshes used to model the 3 arrangements of electrodes (A, B and C). Steady state modelling of electroosmotic flow has been used to shortlist configurations likely to lead to uniform treatments. In arrangement A, flowlines perpendicular to the contours shown in Figure 7 lead to an estimate that half of chemicals will flow through an area of  $0.17 \text{ m}^2$  between the pair of electrodes while the rest will flow through an area of  $0.33 \text{ m}^2$ , i.e. two thirds of the soil will see only half the chemicals that the other one third sees. In other words, arrangement A fails to provide uniform treatment to all soil areas. A similar exercise leads to a similar conclusion for arrangement C, whilst arrangement B leads to a better way of delivering treatments, with potential contours showing flow which is the closest to uniform/one dimensional.

### 4.2 Environmental sustainability considerations

A preliminary LCA of the clay biostimulation experiment was performed using SimaPro software (version 9.1.1), with the EK biocementation treatments used in the bench scale tests of soil MH compared to conventional soil stabilisers such as Portland cement (PC) and hydrated lime (if implemented by EK). The Life Cycle Impact Assessment (LCIA) was conducted using the ReCiPe 2016 Midpoint Hierarchist (H) methodology, developed collaboratively by RIVM, Radboud University, the Norwegian University of Science and Technology, and PRé Sustainability. The primary source for Life Cycle Inventory (LCI) data in this research was the Ecoinvent database. The system boundaries included all processes related to the production of materials but excluded impacts associated with its implementation, as this was assumed to be the same for all solutions. It also excluded transportation and any by-products. The CA metabolic biocementation route is not producing any major harmful byproducts, therefore this was considered as a reasonable assumption. The functional unit adopted in the LCA was 1kg of soil, adopting a cut-off allocation approach for the three systems' environmental impacts.

The results indicated a considerable improvement in terms of  $\text{CO}_2$  emissions and hence global warming potential if CA biocementation is used; namely  $0.00823 \text{ kg CO}_2 \text{ eq}$  for biocement, vs  $0.019342$  and  $0.022136 \text{ kg CO}_2 \text{ eq}$  for Portland cement and hydrated lime respectively, for the system boundaries considered. There was also a better performance of biocement in terms of resource scarcity compared to Portland cement and hydrated lime ( $7.06\text{E-}05 \text{ kg Cu eq}$  compared to  $8.47\text{E-}05$  and  $4.78\text{E-}04$  for PC and lime respectively) and a lower effect of ozone formation in terms of human health and terrestrial ecosystems compared to PC (although marginally higher than lime). The biocementation process was however more water-consuming compared to lime and cement, as more

than one solution in water were used for the biocement. Some other impacts came higher for biocement compared to lime and PC (e.g., terrestrial acidification or fresh and marine water eutrophication and ecotoxicity due to the production of the primary materials used in the biocement solutions, which were slightly lower in PC and lime). However, these could be due to the system boundaries and the processes assumed for the production of the materials used for biocementation, as well as the materials used. For example, the LCA was performed considering  $\text{NaHCO}_3$  as a source of  $\text{CO}_2$ . However, in a future scenario, captured waste  $\text{CO}_2$  from industry could be used; moreover, one way of capturing  $\text{CO}_2$  is to convert it to  $\text{NaHCO}_3$  at the plant, enhancing the sustainability of EK biocementation.

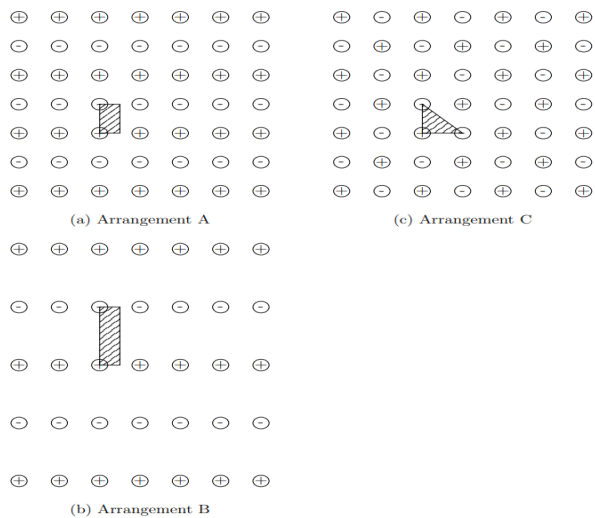


Figure 6. Alternative rectangular grid arrangements of electrodes considered for field testing

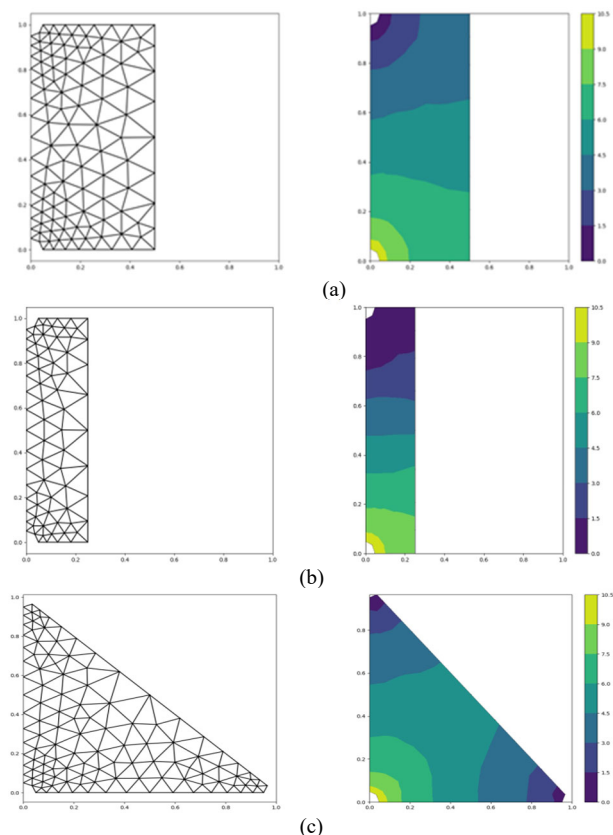


Figure 7. Finite element meshes and electric potential contours for configurations A (a), B (b), & C (c)

## 5 CONCLUSIONS

Tests on the EK biocementation of soft soils from East Anglia showed promise for the feasibility of the technique for these soils as increases in undrained shear strength by 4-10 times higher than the untreated soils and substantial carbonate content increase were noted. This adds to the current limited body of studies, demonstrating feasibility of biocementation in soft fine grained soils and organic soils. The better overall sustainability performance of the technique compared to chemical EK treatment with PC or lime was also demonstrated; this can be further enhanced by introducing waste materials in the biocementation solutions. Overall, the study builds confidence in the techniques towards scaling up for industry adoption - a subject of ongoing work.

## 6 ACKNOWLEDGEMENTS

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