

Influence of water content on the electrical resistivity of biocemented soils investigated through the shape of the water retention curve and considering chemical effects

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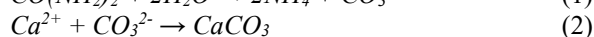
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Abstract. Non-destructive tests, such as geophysical electrical resistivity tests, can be useful to determine how Biocementation treatment in soils is distributed in volume. However, electrical resistivity is affected not only by void ratio but also by water content and the chemical nature of the pore fluid. This paper presents an experimental investigation performed to analyse the changes on the electrical resistivity of a sandy soil after biocementation treatment using enzymes, considering changes on water content. Electrical resistivity measurements were carried out using Wenner method and the water retention curves of the untreated and treated sands were measured using a Water Dewpoint Potentiometer (WP4). The water retention curves for the wetting paths were similar for both the treated and untreated soils, but suction measured during drying in the soil with biocement was higher than that of the untreated soil because of the chemical elements in the pore fluid and the presence of the biocement clogging soil pores. Electrical resistivity measurements do not allow to conclude to what extent the presence of biocement affects the conductivity of electricity through the soil, however electrical resistivity and soil suction are related even in the presence of the pore fluid ions due to the treatment. Detailed study of these parameters could help to understand if this non-destructive technique can be used to monitor biocementation progress in the volume of the treated soil.

1 Introduction

Biocementation consists of using enzymes or bacteria to promote the precipitation of calcium carbonate (biocement) in soil pores [1]. For this purpose, an aqueous solution containing the biological precipitating agent is injected into the soil. Then, a feeding solution, so called because it contains the chemicals with which the biological agents interact to produce the carbonate, is injected into the soil.

In detail, enzymes or bacteria are used to catalyze the hydrolysis of urea ($\text{CO}(\text{NH}_2)_2$) resulting in carbonate ions CO_3^{2-} and ammonium (Eq. (1)). Subsequently, calcium carbonate (CaCO_3) precipitates in the presence of calcium ions Ca^{2+} (Eq. (2)). Both urea and calcium are supplied in the feeding solution.



The success of the technique depends to a large extent on the homogeneity of the distribution of these solutions in the soil, which is directly related to the soil porosity and water content. The changes induced by the treatment in the soil lead to a change in its texture and composition. To check the effectiveness of the treatment, it is necessary to monitor these changes.

Geophysical methods have the advantage over other techniques of being non-destructive. One of the most used in civil engineering is the measurement of the electrical resistivity [2]. Although the results can be difficult to interpret, due to the many variables involved, recent research shows that this technique can be effective in monitoring the efficacy of biocementation treatments [3, 4].

This paper presents an experimental investigation performed to analyse the changes on the electrical resistivity of a sandy soil after the biocementation treatment using enzymes, considering changes on water content and the presence of ions in the pore fluid. The purpose of the study is to understand if this non-destructive technique can be used to monitor biocementation progress in the volume of the treated soil.

2 Methods

2.1 Sand

The soil selected for this study is an uniform-graded quartzitic sand, classified as SP according to the Unified Soil Classification System. The average diameter (D_{50}) is 0.3 mm and its fine content is 2.65%.

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The sand was dried in the oven before being poured in a plastic box (24 cm long, 14 cm wide, and 8 cm high, scheme in Fig. 1) to measure the evolution of the electrical resistivity along a drying path. The dry sand was poured with special care to ensure a final porosity of 43.7% and void ratio (e) of 0.78. No drainage was allowed during the treatment.

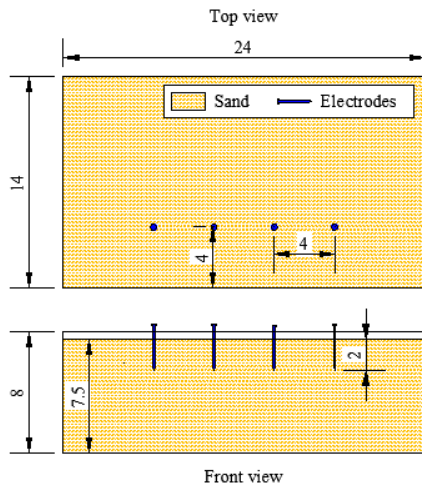


Fig. 1. Sand box layout (units in centimetres).

2.2 Biocementation treatment

Powder urease enzyme obtained from the jack bean plant was used for sand treatment. First, 50 ml solution prepared with distilled water and 3 mg/L of enzyme was sprayed over the sand. Afterwards, 100 ml of feeding solution (FS) was sprayed. The FS was prepared using 0.5 M equimolar solutions of urea and calcium chloride (source of calcium). This treatment was applied once a day for five consecutive days. Spray was applied in the entire area of the box, following a predefined mesh to ensure homogeneity. The treatment fluid was infiltrated in the soil naturally. The total volume of fluids used each day in the treatment was not enough to full saturate the soils, however the final water content at the surface corresponds to a case closer to full saturation ($w_{sat}=28\%$, computed using the void ratio at preparation).

2.3 Electrical resistivity measurements

Wenner method was adopted to measure the electrical resistivity of the treated sand. Four steel electrodes with 3 cm length were inserted through the top of the sand layer, into a depth of 2 cm (Fig. 1). Electrical resistivity measurements were made during the enzyme treatment of the sand by using Eq. 3, where ρ is the apparent resistivity, a is the spacing between electrodes, b is the depth of electrode, and R is the resistance measured. This corresponds to a wetting path because fluid was added during the treatment. After completion, further measurements were made to analyse the variation of electrical resistivity as the sand dried naturally in the laboratory environment ($T=21^\circ\text{C}$, $\text{RH}=54\%$). The water content was determined in small soil samples extracted far from the electrodes, before each electrical resistivity measurement.

$$\rho = \frac{4\pi aR}{1 + \frac{2a}{\sqrt{a^2+4b^2}} - \frac{a}{\sqrt{a^2+b^2}}} \quad (3)$$

The off-center position of the electrodes in the box (see Fig. 1) allows samples to be collected in the area further away from the electrodes without affecting the section of soil that is being crossed by the electric current. This is possible because, in the Wenner method, the measurement obtained is indicative of the average resistivity of the soil hemisphere with a radius equal to the spacing between the electrodes [5].

A power supply was used to apply electrical current (Aim-TTi EX354RD), and a digital multimeter (DT9205A) was used to measure the difference on electrical potential between the inner electrodes.

The measurements were done during the application of the treatment and, after the treatment was finished. In this last case the amount of carbonate present in the soil remains constant and the pore water evaporates naturally (drying curve). No measurements were performed in the untreated sand because the resistivity values were very high due to the absence of chemicals in the distilled water.

2.4 Water and calcium contents

A small sample of soil was collected each time the electrical resistivity was measured, to determine its pore fluid content (called as water content, for simplification). The same sample was used after to measure the precipitated mass of calcium carbonate by using acid digestion [6].

2.5 Suction measurements

For the water retention curve, soil suction was measured using a dew-point Water Potential Meter (WP4). For the natural (untreated) soil, the sand was placed in the sample holder ensuring that the porosity was the same as that of the sand deposited in the box for the electrical resistivity measurements. The biocemented samples were taken from the surface of the sand box after its biological treatment. In both cases, the measurements were made for wetting and drying paths, with the wetting path started from samples dried at environmental conditions.

Experimental data was adjusted using Van Genuchten [7] equation, where s is suction, S_r is the degree of saturation, P is a constant associated to the air entry value (MPa) and y is a constant. Constants P and y are determined numerically.

$$S_r = \left(1 + \left(\frac{s}{P} \right)^{1-y} \right)^{-y} \quad (4)$$

3 Results and discussion

3.1 Calcium carbonate content

The treatment resulted in the formation of a 1,5 cm thick stiff superficial layer, in which the percentage of carbonate content is 4%. The electrodes were inserted in this upper layer. The carbonate content decreased to 2% below this layer and become negligible at 4,0 cm depth. A constant amount of precipitate was assumed in the upper layer where the electrodes are inserted because a stiff layer with approximately 1.5 cm thickness was observed at the end of the experiment.

3.2 Water retention curves

The water retention curves of the treated and untreated soils are presented in Figure 2. The adjustment using Eq. 3 is also presented (untreated soil: $P= 0.51\text{MPa}$ and $y= 0.03$; treated soil $P= 0.58\text{MPa}$ and $y= 0.06$). These parameters were found by minimizing the minimum square error.

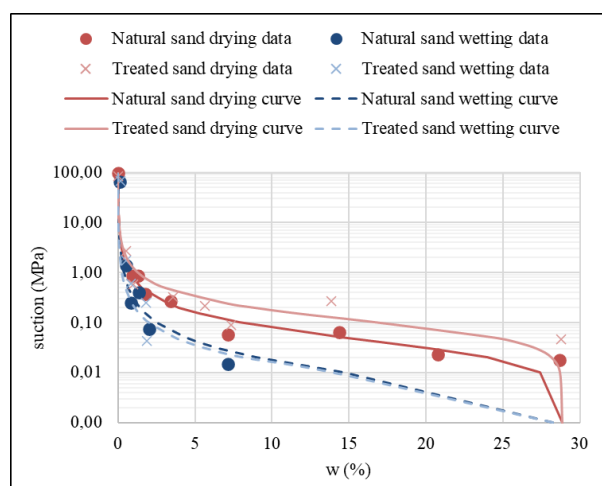


Fig. 2. Water retention curves obtained for the treated and untreated soil.

It was found higher hysteresis for the treated soil when compared to the untreated one, which may be explained by the presence of biocement precipitated in the particles introducing structural changes.

The wetting curves are similar for both treated and untreated cases, however the suction obtained during drying in the soil with biocement is higher than in the untreated one. This can be attributed not only to pore clogging by the calcium carbonate, by also to the presence of by-products of the biochemical reaction (ammonia) in the pore fluid.

Considering the drying paths, the air entry value observed for the treated material is above that of the untreated one. This result can be explained by some pore clogging effect due to the presence of carbonate, or to the influence of the chemicals present in the pore fluid. Indeed, suction measured in the treatment fluid alone was 0.24 MPa, which can contribute to increase suction at for very high values of fluid content, where soil is closer to full saturation.

As expected for granular materials, the curves have an almost flat zone followed by a steep transition to the high suction ranges. Despite these differences, in both the natural and treated soil, the residual water content is about 2%.

3.3 Electrical resistivity

The electrical resistivity values measured for the treated soil are presented in Fig. 3. There is a clear difference between the two curves because they were obtained following different procedures:

(i) The curve corresponding to the case “During the treatment” is a wetting path, where the amount of biocement is increasing as treatment progresses, as well as the degree of saturation.

(ii) The curve corresponding to the case “After treatment” is a drying path for fixed amount of biocement, where the degree of saturation is decreasing. Because drying is caused by evaporation, there is an increase on the concentration of by-products of the biochemical reaction (concentration increases along drying).

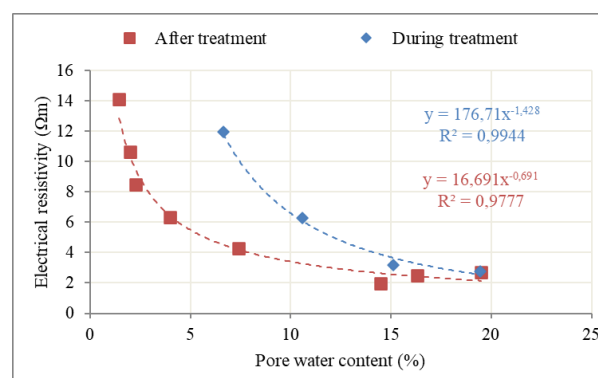


Fig. 3. Variation in electrical resistivity measurements as a function of pore water content during and after the treatment application.

Both curves measured for the treated material confirm that the electrical resistivity depends on water content of the soil, being this dependence more marked for the case after the treatment. This may be explained by the largest concentration of by-products.

The electrical resistivity during the treatment is higher than that after the treatment. Because of the differences in the experimental protocols adopted for both cases, it is not possible to discern to what extent the reduction in electrical resistivity observed for the two cases is only due to the presence of the treatment by-products or if is also affected by the presence of the precipitated carbonate.

3.4 Discussion

The conditions adopted to measure the electrical resistivity curve after the treatment are identical to those adopted to measure the water retention curve, both in the drying paths, and therefore they can be compared. Both suction and electrical resistivity have minimum values when the sand is saturated, gradually increasing as the

pore water content of the soil decreases until a limit value is reached, after which this increase becomes exponential. Although the trend is not the same in both cases, electrical resistivity and soil suction are related at least in the part of the curves for water contents larger than the residual water content (near 2%). These results agree with those obtained by other authors [8, 9].

For the water retention properties of the soil, the presence of biocement increases suction values during the drying curve when compared to those measured in the untreated soil for the same water content. The reduction in soil porosity due to calcium carbonate precipitation means a greater tortuosity of the effective porosity and the need for more energy to extract water from the soil.

The water retention curve shows an inflection point around 2% of the water content, while for the curve showing the variation of electrical resistivity with water content (drying curve), this inflection point occurs for water content around 4%. In case of suction measurements, below such value there is no continuity of the liquid phase and water is mainly adsorbed to the solid phase. For the electrical resistivity, this water content corresponds to the minimum amount of water in the soil necessary to ensure the transmission of electricity through the liquid phase. Nevertheless, they are very similar (the difference may be attributed to experimental error) and were expected, because both behaviours are associated to the degree of saturation of the soil.

The value of the electrical resistivity measured for the full saturated treated soil is much smaller than that of the untreated soil full saturated with tap water, which is 452 Ωm . The value reduces to values closer to 3 Ωm when the soil is saturated with feeding solution without bacteria, which is similar to the value measured for the saturated treated soil (1.7 Ωm). Therefore, the reduction in electrical resistivity is mainly caused by the chemical composition of the pore fluid rather than by the presence of biocement.

Soil structure affects both the water retention and electrical properties of the soil, depending on the presence of biocement. Nevertheless, for the soil studied the amount precipitated was not very high and this may be the reason to not find significant differences between the treated and untreated soil.

4 Conclusions

Biocementation treatment of soils causes structural changes and alters the chemical composition of pore fluid, resulting in changes on soil water retention properties and electrical resistivity. Both are related, as both are dependent on water content or degree of saturation, and on soil structure.

These measurements are conditioned by different variables: the increase in carbonate content as the treatment is prolonged, the increase in the degree of saturation and the presence of by-products derived from the treatment.

Apparently, the presence of biocement in the soil leads to a reduction of its electrical resistivity. However,

a more exhaustive study (currently underway) is necessary to better understand this phenomenon.

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