Large-scale soil improvement tests using microbially induced carbonate precipitation

Rebecca J. Lunn, James M. Minto, Grainne El Mountassir, Mary Anderson

Department of Civil and Environmental Engineering, University of Strathclyde, Glasgow G1 1XJ, UK

Abstract

Bacterial biomineralization provides a greener solution to a diverse range of civil engineering applications, reducing the carbon footprint of construction. Most successful to-date is microbially induced carbonate precipitation (MICP). MICP is being developed for a diverse range of applications including plugging fractures, stabilising soils and repairing building surfaces. In MICP, bacteria are injected within the soil, followed by injection of a fluid containing urea and calcium chloride. The bacteria hydrolyse the urea, which generates bicarbonate ion, increases pH and precipitates calcite. Advantages of MICP include: better penetration due to the low viscosity of the fluids, the ability to maintain free drainage in treated materials and the thousand-year durability of calcite.

Despite the growing interest in MICP for geotechnical applications, MICP still remains largely confined to the laboratory with only a very small number of large-scale experiments having been completed and one commercial project. Use is constrained by (1) the ability to grow bacteria at a commercial scale and (2) the need to ensure homogeneous soil strengthening at a large-scale. In this research, conducted in collaboration with BAM Nuttall, we present the results of large-scale test for MICP treated sand. We treat a 1 m diameter cylinder of loose sand using multiple cycles of MICP. Unconfined compressive strength tests and triaxial tests of cores taken from the treated sand result in strengths of several MPa. Our results show that bacterial biomineralization could be a viable, low carbon alternative to cement and concrete for a range of earth infrastructure applications.

Introduction

Bacterial biomineralization provides a greener solution to a diverse range of civil engineering applications, reducing the carbon footprint of construction. Most successful to-date is microbially induced carbonate precipitation (MICP). MICP is being developed for a diverse range of applications including plugging fractures [1], stabilising soils [2] and repairing buildings [3] . In MICP, bacteria are injected within the soil, followed by injection of a fluid containing urea and calcium chloride. The bacteria hydrolyse the urea, which generates bicarbonate ions, increases pH and results in the precipitation of calcite [4]. Advantages of MICP include: better penetration due to the low viscosity of the fluids, the ability to maintain free drainage in treated materials and the thousand-year durability of calcite.

Despite the growing interest in MICP for geotechnical applications, MICP still remains largely confined to the laboratory with only a very small number of large-scale experiments having been completed [5][6] and one commercial project. Use is constrained by (1) the ability to grow bacteria at a commercial scale and (2) the need to ensure homogeneous soil strengthening at a large-scale. In this research, conducted in collaboration with construction and civil engineering company BAM Nuttall, the results of a large-scale test for MICP treated sand is presented. A 1 m diameter cylinder of loose sand is treated using multiple cycles of MICP. Unconfined compressive strength tests and triaxial tests of cores taken from the treated sand result in strengths of several MPa. These results show that bacterial biomineralization could be a viable, low carbon alternative to cement and concrete for a range of earth infrastructure applications.

Materials and Methods

A radial flow cell was constructed to allow MICP treatment in sand/soil with radial injection strategies similar to those that would be used in the field (Figure 1, left). The sand was added gradually and continuously compacted by hand in the cell whilst underwater. The average initial dry density was 1581 kg/m^3, based on the total mass of sand added, with an average porosity of 40.0%. A first run has been completed in which bacteria were injected at a high flow rate so as to prevent attachment (and hence clogging due to $CaCO_3$ precipitation) near the central injection point where velocities are highest. The volume of bacteria injected in each treatment cycle was approximately half the liquid volume of the cell (i.e. 0.5 Pore Volumes) so that we could evaluate the radial extent of treatment. In total, 1PV of 0.5 M urea/$CaCl_2$ cementing solution was injected, at a lower flow rate, in two stages (i) 0.5 PV injection two hours after the bacteria were injected, and (ii) a further 0.5 PV injection the following morning after an overnight static reaction period. In this way, the cementing solution injection was also used to monitor changes in permeability due to $CaCO_3$ precipitation.

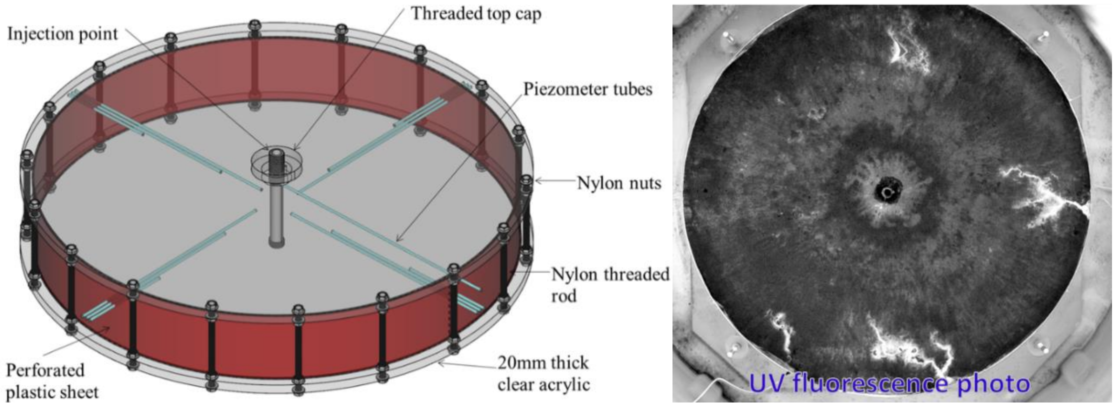

Figure 1. Left: 1m radial flow cell design. Right: overhead UV fluorescence photo taken after treatment of the sand showing high $CaCO_3$ concentrations in white, and low $CaCO_3$ concentration sand as black.

The cell was packed with loose sand. Nine treatment cycles were conducted over nine days, $CaCO_3$ was precipitated over a large proportion of the flow cell. This was visible on the top surface of the sand by using an ultra-violet light source and photographing the fluorescence of the $CaCO_3$ (Figure 2, right). There was less $CaCO_3$ in a ring around the injection point and also close to the outer edge of the flow cell.

Results and Discussion

The initial permeability of the sand was 1.3x10^{-11} m^2 (typical of a medium sand, well sorted) reducing to 7.9x10^{-12} m^2 (typical of a fine sand, well sorted) after the nine treatment cycles and the maximum pressure at any point during treatment was only 6.8 kPa, equivalent to a pressure head of 0.7 m of water. This indicates that the sand remains free-draining after treatment and confirms that low pressure equipment can be used for field-scale MICP treatment.

The MICP treatment of the (originally loose) sand resulted in sufficient cementation, in the area between the two dashed lines in Figure 2, that cores could be drilled for UCS testing. Cores were cut from the block of treated sand using a water-cooled concrete corer. The area between the two dashed circles in Figure 2 (Left) was well cemented and solid enough to stand on whilst coring.

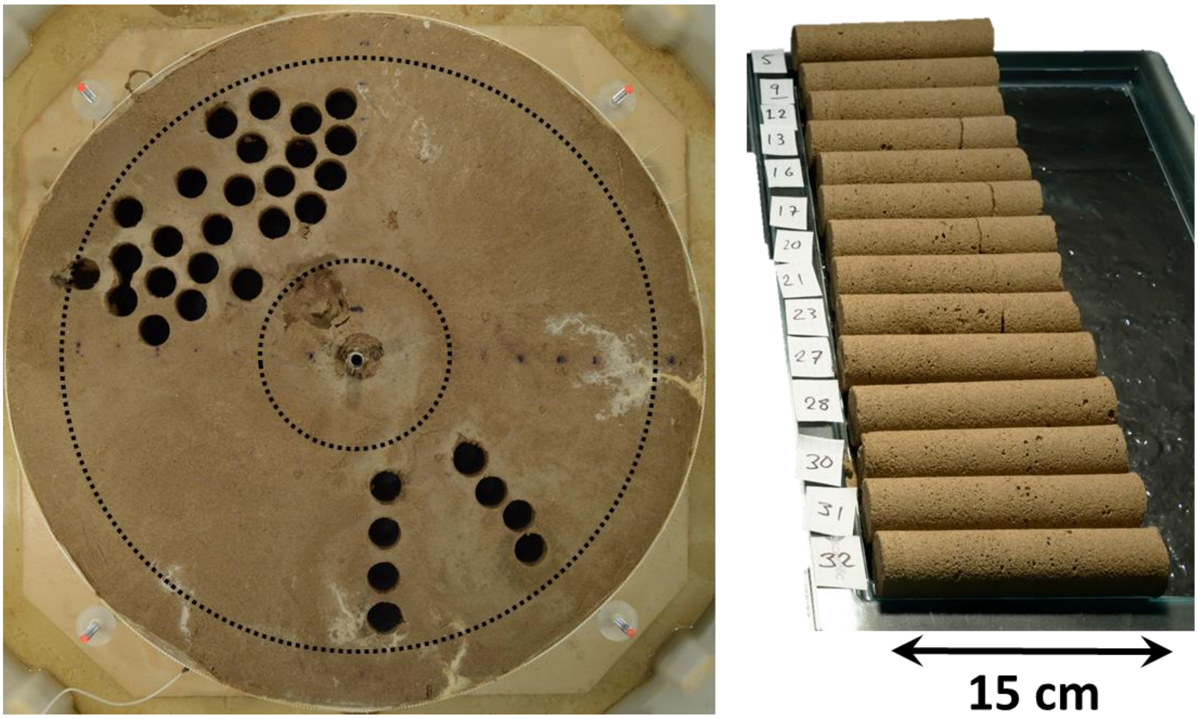

Figure 2. Left: Overhead photo of treated sand after 36mm diameter cores cut. Area between dashed circles was well cemented with $CaCO_3$. Right: cores retrieved for further testing.

Cores were scanned with 2D X-ray radiography showing average density variations with depth, then cut in half (giving a 2:1 length to diameter ratio) and ends were filed smooth and planar. Approximately three quarters of the cores were capped with a high strength plaster in accordance with the standard method ASTM C617/C617M-15. The remaining cores were tested with an unbonded rubber pad, in accordance with ASTM C1231/C1231M-15. Selected cores were then scanned with 3D X-ray tomography giving a detailed map of sample density. All cores were subjected to unconfined compressive strength testing and the maximum load at failure recorded.

Figure 3 shows results for Core 9 in which there was a clear contrast in density between the lower third of the core and the upper two thirds. This contrast in density is thought to be due to the method of compacting the sand under partially saturated conditions and the vertical migration of fine particles during initial placement and compaction, rather than during MICP treatment. In future experiments the sand will be emplaced under fully saturated conditions. Core 9 (Figure 3) had a compressive strength of 4.86 MPa and failure occurred in the high porosity top region (Figure 3 C to E). To put this in context, the 36 mm diameter sample could support up to a 504 kg weight before failing.

Figure 4 shows the relationship between strength and post-treatment dry density for each 2:1 core sample along with the results from [5] which is the only comparable large-scale experiment. The unbonded capping method appears to result in lower strength and this was observed to be due to lateral expansion of the rubber pad hence, for MICP samples, use of bonded caps is preferable. In general, we achieve higher strengths for a lower dry density (which correlates with lower amounts of $CaCO_3$) and in less time than van Paassen indicating more efficient MICP treatment, although we also use a greater amount of bacteria. The greater spread in the data is thought to be due to heterogeneities in the initial sample dry density which are visible in the X-CT data (Figure 3); future tests in which the sand is placed under fully saturated conditions are expected to show a stronger correlation between dry density and strength.

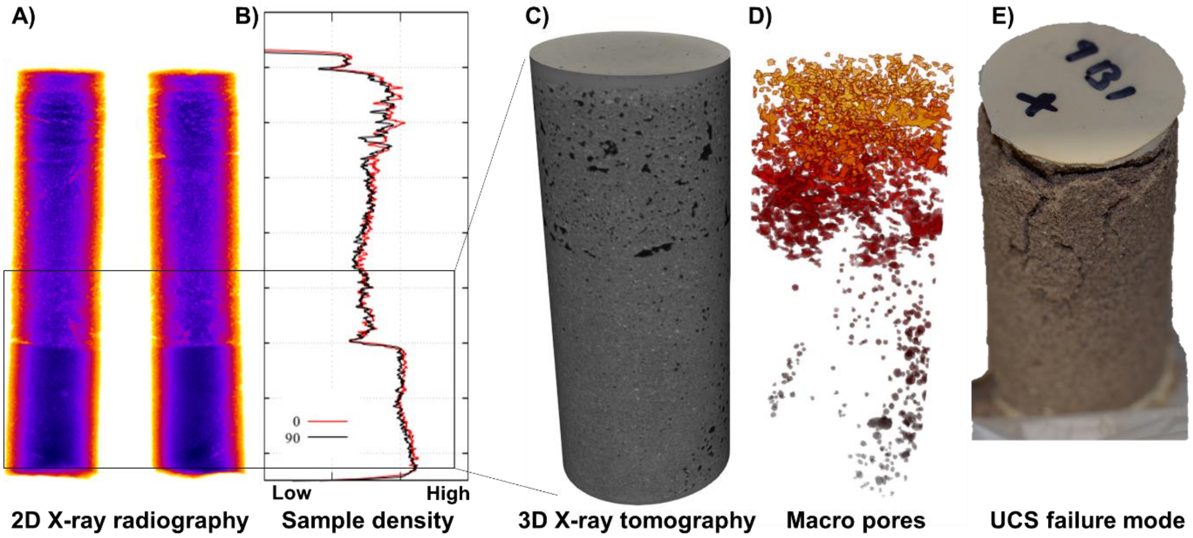

Figure 3. Radial flow cell core analysis. A) 2D X-ray scans at two orthogonal planes and B) corresponding average density profile with depth. C) 3D X-ray scan of the 2:1 core capped and prepared for UCS testing. D) Macro-pore distribution within the sample. E) Failure mode after UCS testing.

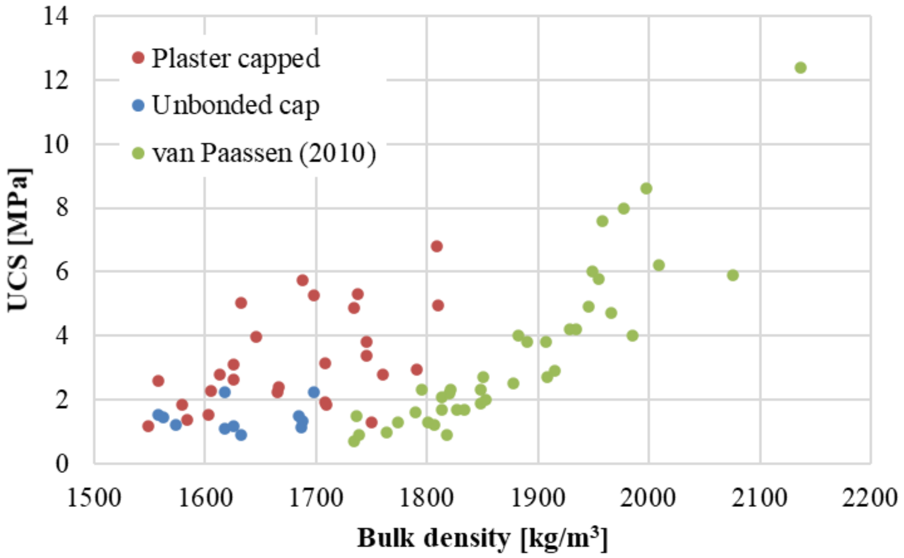

Figure 4. Unconfined compressive strength results for our cores with bonded plaster and unbonded capping methods. Results are shown in comparison to the large scale test carried out by van Paassen [5].

Conclusions

In this research the results of a large-scale test for MICP treated sand are presented. A 1 m diameter cylinder of loose sand is treated using multiple cycles of MICP. Unconfined compressive strength tests and triaxial tests of cores taken from the treated sand result in strengths of several MPa. These strengths exceed those obtained by previous researchers, when plotted against final bulk density of the treated material. Our results show that bacterial biomineralization could be a viable, low carbon alternative to cement and concrete for a range of earth infrastructure applications.

References

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