Proceedings of the 9ICEG
9th International Congress on Environmental Geotechnics
25-28 June, 2023 | Chania, Greece

https://doi.org/10.53243/ICEG2023-122

Self-recovery of soil shear strength by microcapsules: a review of potential cargos and encapsulation methods

Rui Qi[1], Sérgio D.N. Lourenço[2], Antonios Kanellopoulos[3], and Qingjie Yang[4]

[1] PhD Student, The University of Hong Kong, Hong Kong S.A.R., China, email: ruiqi000@connect.hku.hk

[2] Associate Professor, The University of Hong Kong, Hong Kong S.A.R., China, email: lourenco@hku.hk

[3] Associate Professor, University of Hertfordshire, Hertfordshire, UK, email: a.kanellopoulos@herts.ac.uk

[4] PhD Student, The University of Hong Kong, Hong Kong S.A.R., China, email: yangqj@connect.hku.hk

ABSTRACT

Soil settlement leads to serviceability issues of ground infrastructure and is a threat to the stability of overlying structures. To recover the soil shear strength, microcapsules-based self-healing materials are proposed. The purpose of this paper is to review the various cementing cargos with a greater potential to be applied in soils. At first, the review briefly introduces microcapsules-based self-healing materials, the application of microcapsules in other engineering fields, and the significance and importance of applying self-healing approaches to ground engineering. Secondly, a summary of cementing cargos for soil stabilization is provided, including their properties and their effect on soil reinforcement. Finally, the last section discusses the encapsulation methods and corresponding cargos with the greatest potential to be applied to soil shear strength recovery.

Keywords: microcapsules, soil, shear strength recovery

1 INTRODUCTION

Excessive soil settlement leads to serviceability issues in structures due to excessive primary and secondary consolidation, shrinkage of clay and formation of desiccation cracks, and damage of drainage and pipeline systems (Ike, 2005; Tsige et al., 2022). Such undesired effects can be minimized through the implementation of various ground improvement measures including compaction and soil stabilization with cementitious materials (Firoozi et al., 2017; Guetif et al., 2007). However, ground improvement methods cannot be used to 'repair' soils due to their disruptive nature and limited accessibility for maintenance (Harbottle et al., 2014). Therefore, other methods should be developed to recover soil shear strength, arrest soil deformation, and alleviate the damage of structures.

There has been an ongoing interest in applying self-healing materials to repair the damage or recover the performance of degraded materials. Self-healing materials refer to the type of material that can fully or partially recover a functionality that is mediated by operational use without human intervention (Bekas et al., 2016; Kanellopoulos, 2022). Typical self-healing materials include microcapsules and hollow fibbers (Huang et al., 2010; Zhu et al., 2015). Self-healing materials have been applied in various types of infrastructure. Microcapsules-based self-healing materials have been synthesized to repair the microcracks and recover the mechanical strength of concrete (Alghamri et al., 2016). With the application of microcapsules, past results show a strength recovery of approximately 80% (Alghamri et al., 2016). Cargos of microcapsules used for concrete include polyurethane, epoxy resin, sodium silicate, and bacterial spores, among others. The repairing mechanism of polyurethane and epoxy resin is based in the polymerization and hardening of the cargo which fills micro-cracks in concrete (Feiteira et al., 2016; Haiyan et al., 2012). For microcapsules with sodium silicate cargos, the healing property is based on the reaction between sodium silicate and calcium cations (Alghamri et al., 2016; Huang et al., 2011). For microcapsules with bacterial spores, cracking was repaired by the precipitation of calcium carbonate (Wang et al., 2014). In asphalt, sunflower oil has been encapsulated and applied in pavements and increased the crack-healing properties of asphalt (Norambuena-Contreras et al., 2019).

More recently, there have been developments on the application of microcapsules in cemented soils. Urea-formaldehyde microcapsules were fabricated by *in-situ* polymerization and mixed with cemented coral sand. The results indicate that the microcapsules can release their cargo when intersected by cracks or subjected to compression, leading to the filling and self-healing of the internal cracks (Xu et al., 2020). Microcapsules with a sodium silicate cargo were synthesized and their self-healing performance in a soil-cement mix cutoff wall was demonstrated. The embedded microcapsules were opened during cracking, releasing sodium silicate and healing the cracks with a 44% increase of its initial compressive strength (Cao et al., 2021). In other relevant studies, a retention criterion has been proposed for microcapsules mixed with granular soils under the influence of seepage (Chen et al., 2023).

This review takes inspiration from research on self-healing approaches in cementitious materials and aims to investigate the potential cargo and encapsulation methods for soil shear strength recovery by microcapsules. The potential cargo, their properties, and past studies on soil stabilization were summarized. Besides, the potential methods to encapsulate the cargo were discussed.

2 CORE MATERIALS

The function of microcapsules' cargos is to improve the soil geotechnical properties to meet engineering purposes (Afrin, 2017; Eme & Agunwamba, 2014; Tan et al., 2020). Soil stabilizers are potential candidates for microcapsules cargos and divide into calcium-based stabilizers, which include cement, lime, and fly ash, and other chemical stabilizers, including silica-based, polymer emulsions, and hardening oils. The properties of the stabilizers are presented in this section.

2.1 Calcium-based stabilizers

Powdered cement and lime are the most frequently used traditional chemical stabilizers (Tan et al., 2020). Cement can be used to improve the soil strength and stiffness (Ramaji, 2012). Cement stabilization is applicable to most soils as the hydration reaction is not dependent on the water rather than the type of soil minerals (Afrin, 2017). Past studies showed soil stabilization by cement for sandy soils (Kennedy et al., 1987), clayey soils (Prusinski & Bhattacharja, 1999), and peat (Boobathiraja et al., 2014). However, cement-based stabilization is not suitable in some conditions. For organic soils, the organic content affects the hydration reaction and decreases the soil stabilization strengths (Skels et al., 2013; Tan et al., 2020; Zulkifley et al., 2014). Also, For soils with pH less than 5.5, The hydration reaction is retarded, resulting in slower soil strength after the stabilization (Skels et al., 2013; Tan et al., 2020). Lime is another type of calcium-based soil stabilizer which is a white or greyish-white, odorless, lumpy, very slightly water-soluble solid (Ramaji, 2012). The quicklime (CaO) can react with water and form slaked lime ($Ca(OH)_2$). Both can be used for soil stabilization. The mechanism of lime based soil modification is based on cation exchange capacity, which transfers the soil structure and increases the soil strength(Afrin, 2017; Sherwood, 1993). Lime is suitable for the stabilization of clayey soils with medium to high plasticity but less suitable for granular soils (Little, 1995; Negi et al., 2013; Petry & Lee, 1988).

2.2 Silica-based stabilizer

Silica-based soil stabilizer include sodium silicate and colloidal silica. Colloidal silica is an aqueous dispersion of silica nanoparticles with low initial viscosity and it is applied for grouting in soils and fractured rock (Wong et al., 2018). The colloidal silica was used in sandy soils and increased the unconfined compression test strength to 0.41 MPa (Persoff et al., 1999). Sodium silicate consists of silicate monomers and is considered as non-hazardous and environmentally safe. Sodium silicate have a higher viscosity compared to colloidal silica. The sodium silicate is proven to increase the strength of sand (Maher et al., 1994) but is less effective for organic soils (Kazemian et al., 2012). The mechanism of silica based soil stabilization is the reaction between silicate and calcium salt in soil or groundwater, which form calcium silicate and bonds the soil particles together. (Hurley & Thornburn, 1971).

2.3 Resins and polymers

Resins are applied to soils for mechanical improvement and waterproofing (Spagnoli, 2018). The main categories of resins are epoxy and polyurethane, which improve soil strength by forming strong polar bonds with the surfaces of soil particles it comes in contact with (Spagnoli, 2018). The resin showed a strength enhancement in sand, which had an 8 MPa UCS value after 90 days of curing. Polymers were employed for the stabilization of bored piles. Past studies invested the soil strength increase by the addition of various polymers, including vinyl acetate, acrylic-based copolymer latexes, and styrene-butadiene (SB) copolymer latex (Ohama, 1998). By mixing polymer with silty sand and curing for 28 days, the soil samples have an average of 3.5 MPa UCS strength. The advantage of polymers-based stabilizers is that they have a strong cohesive strength and are non-polluting. However, the polymers are less effective to coat on the surface of fine-grained soils, and are limited to use in sandy soil (Tingle et al., 2007).

2.4 Hardening oils

The hardening of oils refers to the process of converting unsaturated esters of fatty acids into saturated esters by hydrogenation. One of the most common hardening oils is tung oil, which is obtained from the seeds of the tung tree. Ecotoxicity assessments revealed that tung oil had a minimal impact on soil microorganisms and was safe to use in soils (Lin et al., 2022). As fatty acids with multiple conjugated double bonds, the tung oil undergoes polymerization when exposed to air, which transfers from a liquid form into hard films (Dodiuk, 2021). As the tung oil was mixed with soil, the hardening of tung oil can effectively bond the soil particles, which contributes to soil cohesion and leads to a remarkable increase in the unconfined compressive strength of the soils (Lin et al., 2021).

3 ENCAPSULATION METHODS

3.1 Physical methods

Pan coating and spray drying are the most common physical encapsulation methods. Pan coating is applied to create another shell on the surface of solid tablets, which is the oldest encapsulation technique. The shell of the microcapsule is produced by spraying the liquid form through a pressure nozzle, and the hardening of the shell through raising the environment temperature. The size of microcapsules produced by pan coating depends on the size of the solid tablets and is typically larger than 1 mm (de Koster et al., 2015). Smaller sizes can be reached by controlling the spraying of liquid and the rotation speed. Cement and lime are solid cargos and can be encapsulated with pan coating method. Figure 1 shows the microcapsules with cement cargo encapsulated with the pan coating method.

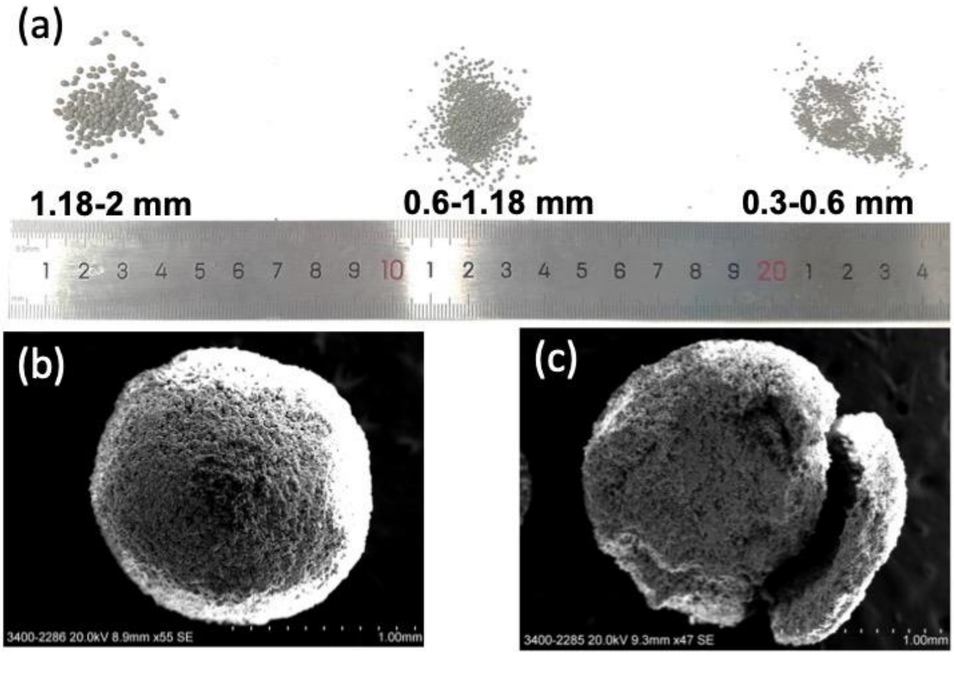

Figure 1. *Microcapsules produced by the pan coating method: (a) Photographs of microcapsules with cement cargo; (b) SEM image of microcapsule with cement cargo; (c) SEM image of ruptured microcapsule with cement cargo.*

3.2 Chemical methods

Interfacial polymerization and *in suit* polymerization are the most common physical encapsulation methods. The chemical encapsulation methods involve polymerization reactions to form the shell of the microcapsules. The lipophilic monomers are dispersed in oil, which is typically used as cargo. The hydrophilic monomers are dispersed in aqueous solutions. By emulsifying the cargo into aqueous solutions, the polymerization happened at the interface of the oil-in-water surface, which formed the shell of the microcapsules (Kanellopoulos et al., 2017). The reaction of *in suit* polymerization happened in the continuous phase, and there are no reactants in the core material. The polymerization of *in suit* polymerization method is typically triggered by the pH conditions of the continuous phase. The typical shell formed by *in suit* polymerization includes urea-formaldehyde, melamine-formaldehyde, and urea-melamine-formaldehyde (Bakry et al., 2016; Bruyninckx & Dusselier, 2019; Kanellopoulos et al., 2017). Figure 2 (a) and (b) shows epoxy resin and tung oil encapsulated by the *in-situ* polymerization method with a urea-formaldehyde shell. A silicon-based cargo can also be encapsulated with the interfacial polymerization method. Sodium silicate has been encapsulated with the interfacial polymerization technique with a polyurea shell, as shown in Figure 2 (c) and (d). The results suggested that the cargo content (sodium silicate content) of the microcapsules could reach around 90% (Mao et al., 2020).

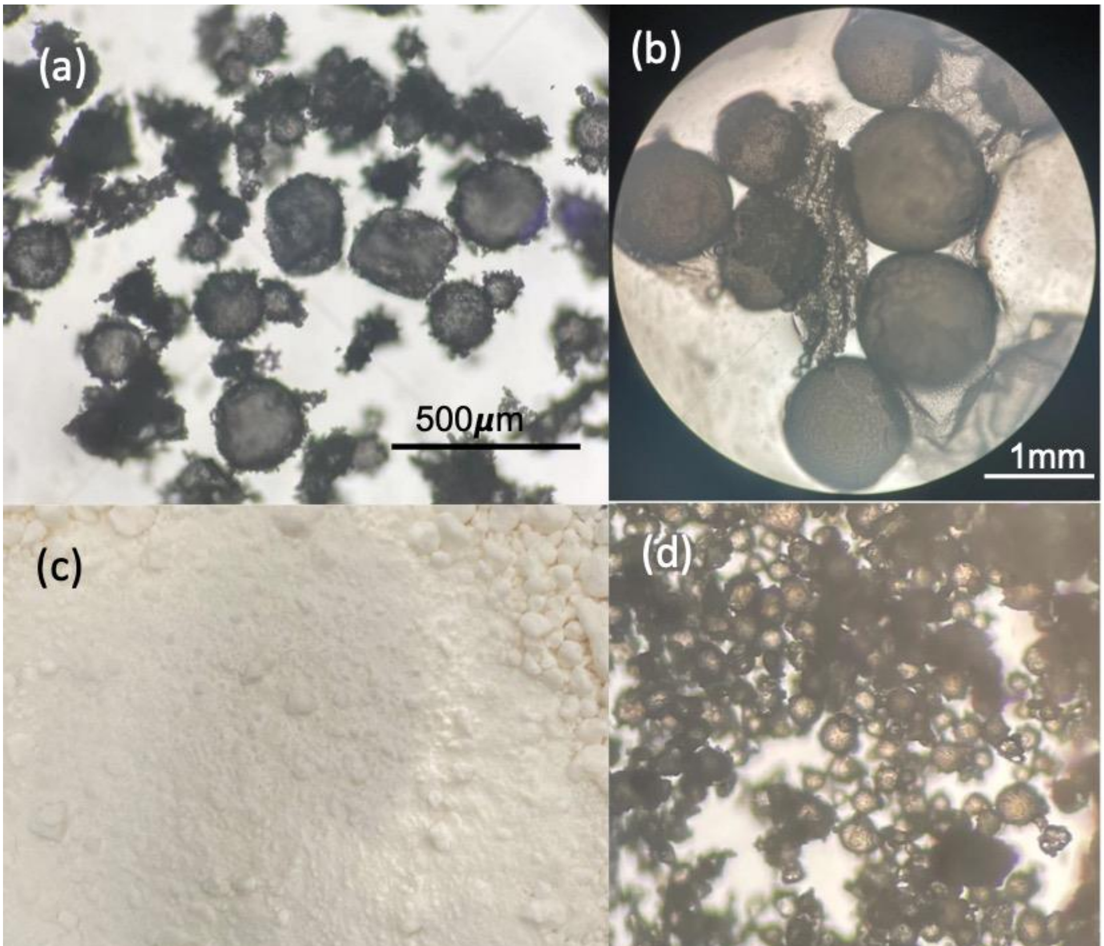

Figure 2. *Microcapsules with various cargo produced by chemical methods: (a) microphotograph of microcapsules with epoxy resin cargo produced by the in-situ polymerization method; (b) microphotograph of microcapsules with tung oil cargo produced by the in-situ polymerization method; (c) microcapsules with sodium silicate cargo produced by the interfacial polymerization method; (d) microcapsules with sodium silicate cargo produced by the interfacial polymerization method.*

3.3 Physiochemical methods

Complex coacervation is one of the physiochemical encapsulation techniques and popular in the food industry. The shell of microcapsules forms through the polymerization of two differently charged polymers. The typical polymers used for complex coacervation are gum arabic and gelatin. It produced a shell that is non-toxic and biodegradable. The advantage of complex coacervation is that it has a high encapsulation efficiency of cargos, reaching up to 99% (Timilsena et al., 2019). Complex coacervation can be applied to encapsulate: (1) hardening oils, which form the shell in the interface of oil and water phase (Timilsena et al., 2019), as shown in Figure 3 (a) and (b); (2) calcium-based powders, by dispersing the powder into oils and form microcapsules; (3) silica-based stabilizers, which form a water in oil emulsion and from the shell in the surface of the emulsion (Kanellopoulos et al., 2017), as shown in Figure 3 (c) and (d). Figure 3 (e) and (f) shows the SEM of microcapsules produced by the complex coacervation method.

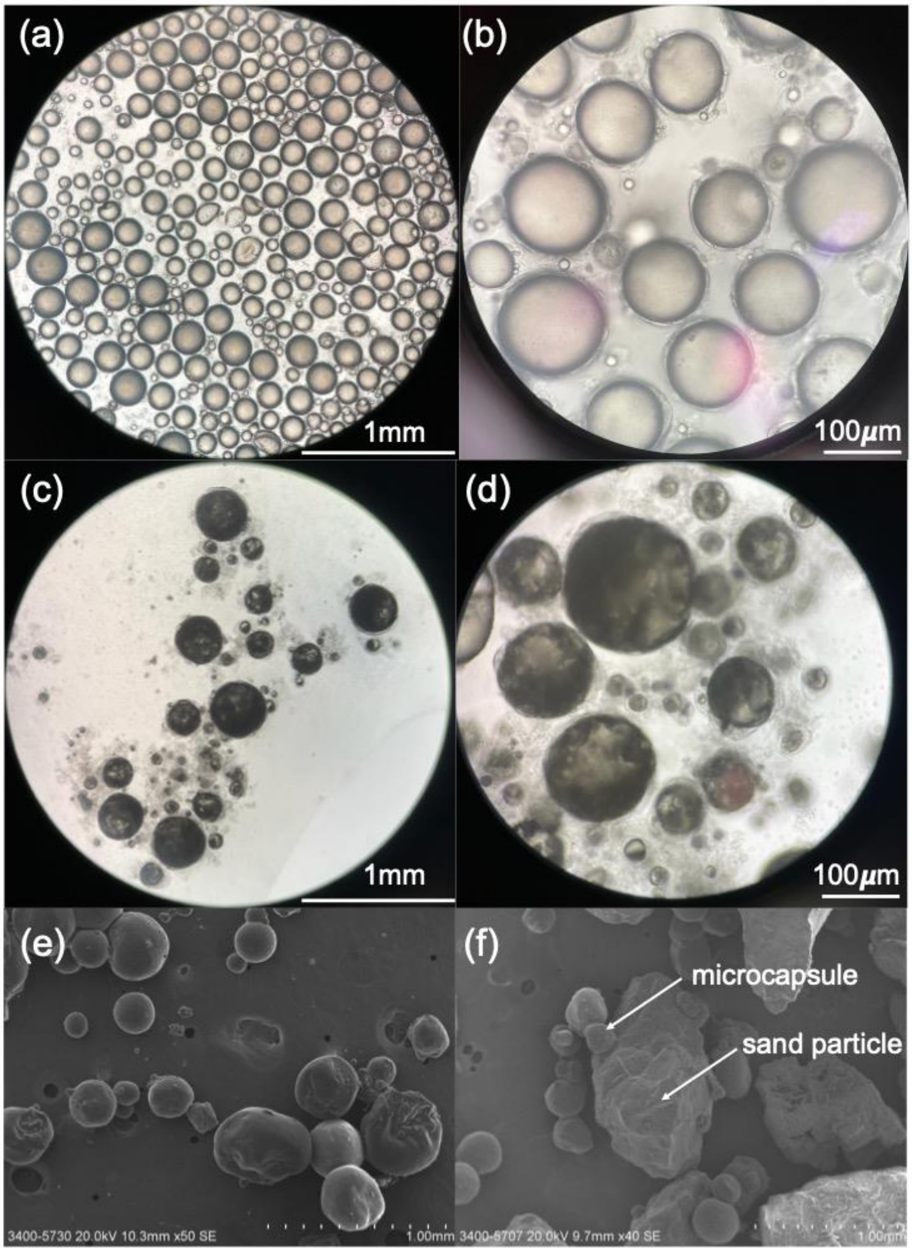

Figure 3. *Microcapsules with various cargo produced by the complex coacervation method: (a) and (b) microcapsules with tung oil cargo; (c) and (d) microcapsules with sodium silicate cargo; (e) SEM image of microcapsules with tung oil cargo; and (f) SEM image of microcapsules with tung oil cargo mixed with sand particles.*

4 CONCLUSIONS AND FUTURE WORK

This review synthesizes the properties of potential cargos for soil shear strength recovery and presents the various encapsulation methods, encapsulation mechanism, and microcapsules properties used in allied fields. Soil stabilizers used in past research can be categorized into calcium-based stabilizers, silica-based stabilizers, resins and polymers, and hardening oils. The effects on soil shear strength increase of the stabilizers depend on the soil types. As a result, the soil types should be considered in the selection of microcapsules cargos. The encapsulation methods can be classified into physical, chemical, and physiochemical methods. So far, the application of microcapsules-based healing material is limited on cemented soils, which have similar properties to cementitious materials. For the application of microcapsules-based healing materials on soils, future work could encompass: (1) testing the encapsulation performance of various cargos that have been used in soil stabilization, (2) characterization of properties of the selected microcapsules, and (3) testing the mechanical properties recovery of different types of soils with suitable microcapsule.

5 ACKNOWLEDGEMENTS

This work was supported by a Collaborative Research Fund from the Research Grants Council Hong Kong (C6006-20GF), a seed funding grant from The University of Hong Kong (201910159115) and Royal Society International Exchanges 2020 R3(IES\R3\203024).

REFERENCES

Afrin, H. (2017). A review on different types soil stabilization techniques. *International Journal of Transportation Engineering and Technology*, *3*(2), 19-24.

Alghamri, R., Kanellopoulos, A., & Al-Tabbaa, A. (2016). Impregnation and encapsulation of lightweight aggregates for self-healing concrete. *Construction and Building Materials*, *124*, 910-921. https://doi.org/10.1016/j.conbuildmat.2016.07.143

Bakry, A. M., Abbas, S., Ali, B., Majeed, H., Abouelwafa, M. Y., Mousa, A., & Liang, L. (2016). Microencapsulation of oils: A comprehensive review of benefits, techniques, and applications. *Comprehensive reviews in food science and food safety*, *15*(1), 143-182.

Bekas, D., Tsirka, K., Baltzis, D., & Paipetis, A. S. (2016). Self-healing materials: A review of advances in materials, evaluation, characterization and monitoring techniques. *Composites Part B: Engineering*, *87*, 92-119.

Boobathiraja, S., Balamurugan, P., Dhansheer, M., & Adhikari, A. (2014). Study on strength of peat soil stabilised with cement and other pozzolanic materials. *International Journal of Civil Engineering Research*, *5*(4), 431-438.

Bruyninckx, K., & Dusselier, M. (2019). Sustainable chemistry considerations for the encapsulation of volatile compounds in laundry-type applications. *ACS Sustainable Chemistry & Engineering*, *7*(9), 8041-8054.

Cao, B., Souza, L., Xu, J., Mao, W., Wang, F., & Al-Tabbaa, A. (2021). Soil Mix Cutoff Wall Materials with Microcapsule-Based Self-Healing Grout. *Journal of Geotechnical and Geoenvironmental Engineering*, *147*(11), 04021124.

Chen, K., Qi, R., Xing, X., Sufian, A., & Lourenço, S. D. N. (2023). Constriction size retention criterion for calcium alginate microcapsules in granular materials. *Powder Technology*, *413*, 118034. https://doi.org/https://doi.org/10.1016/j.powtec.2022.118034

de Koster, S. A. L., Mors, R. M., Nugteren, H. W., Jonkers, H. M., Meesters, G. M. H., & van Ommen, J. R. (2015). Geopolymer Coating of Bacteria-containing Granules for Use in Self-healing Concrete. *Procedia Engineering*, *102*, 475-484. https://doi.org/10.1016/j.proeng.2015.01.193

Dodiuk, H. (2021). *Handbook of thermoset plastics*. William Andrew.

Eme, D., & Agunwamba, J. (2014). Tensile strength of natural and lime stabilized clay soil in Rivers State using one indirect tensile testing technique (Splitting test). *Int. J. Eng. Sci*, *3*(4), 38-45.

Feiteira, J., Gruyaert, E., & De Belie, N. (2016). Self-healing of moving cracks in concrete by means of encapsulated polymer precursors. *Construction and Building Materials*, *102*, 671-678.

Firoozi, A. A., Guney Olgun, C., Firoozi, A. A., & Baghini, M. S. (2017). Fundamentals of soil stabilization. *International Journal of Geo-Engineering*, *8*(1), 1-16.

Guetif, Z., Bouassida, M., & Debats, J. (2007). Improved soft clay characteristics due to stone column installation. *Computers and Geotechnics*, *34*(2), 104-111.

Haiyan, L., Rongguo, W., & Wenbo, L. (2012). Preparation and self-healing performance of epoxy composites with microcapsules and tungsten (VI) chloride catalyst. *Journal of reinforced plastics and composites*, *31*(13), 924-932.

Harbottle, M. J., Lam, M. T., Botusharova, S. P., & Gardner, D. R. (2014). Self-healing soil: Biomimetic engineering of geotechnical structures to respond to damage. International Congress on Environmental Geotechnics,

Huang, C. Y., Trask, R. S., & Bond, I. P. (2010). Characterization and analysis of carbon fibre-reinforced polymer composite laminates with embedded circular vasculature. *J R Soc Interface*, *7*(49), 1229-1241. https://doi.org/10.1098/rsif.2009.0534

Huang, H., Ye, G., Leung, C., & Wan, K. (2011). Application of sodium silicate solution as self-healing agent in cementitious materials. International RILEM conference on advances in construction materials through science and engineering,

Hurley, C. H., & Thornburn, T. H. (1971). *Sodium silicate stabilization of soils: A review of the literature*. Soil Mechanics Laboratory, Department of Civil Engineering, Engineering ….

Ike, C. C. (2005). *PRINCIPLES OF FOUNDATION ENGINEERING*. PRINCIPLES OF FOUNDATION ENGINEERING.

Kanellopoulos, A. (2022). *Self-Healing Construction Materials: Fundamentals, Monitoring and Large Scale Applications*. Springer Nature.

Kanellopoulos, A., Giannaros, P., Palmer, D., Kerr, A., & Al-Tabbaa, A. (2017). Polymeric microcapsules with switchable mechanical properties for self-healing concrete: synthesis, characterisation and proof of concept. *Smart Materials and Structures*, *26*(4), 045025.

Kazemian, S., Prasad, A., Huat, B. B., Ghiasi, V., & Ghareh, S. (2012). Effects of cement–sodium silicate system grout on tropical organic soils. *Arabian Journal for Science and Engineering*, *37*(8), 2137-2148.

Kennedy, T. W., Smith, R., Holmgreen Jr, R. J., & Tahmoressi, M. (1987). An evaluation of lime and cement stabilization. *Transportation research record*(1119).

Lin, H., Liu, F. Y., Lourenço, S. D. N., Schwantes, G., Trumpf, S., Holohan, D., & Beckett, C. T. S. (2021). Stabilization of an earthen material with Tung oil: compaction, strength and hydrophobic enhancement. *Construction and Building Materials*, *290*. https://doi.org/10.1016/j.conbuildmat.2021.123213

Lin, H., Weitz, H. J., Paton, G. I., Hallett, P. D., Hau, B. C., & Lourenço, S. D. (2022). Ecotoxicity assessment of hydrophobized soils. *Environmental Geotechnics*, 1-8.

Little, D. N. (1995). *Stabilization of pavement subgrades and base courses with lime*.

Maher, M., Ro, K., & Welsh, J. (1994). Cyclic undrained behavior and liquefaction potential of sand treated with chemical grouts and microfine cement (MC-500). *Geotechnical Testing Journal*, *17*(2), 159-170.

Mao, W., Litina, C., & Al-Tabbaa, A. (2020). Development and application of novel sodium silicate microcapsule-based self-healing oil well cement. *Materials*, *13*(2), 456.

Negi, A. S., Faizan, M., Siddharth, D. P., & Singh, R. (2013). Soil stabilization using lime. *International journal of innovative research in science, engineering and technology*, *2*(2), 448-453.

Norambuena-Contreras, J., yalçın, E., Hudson-Griffiths, R., & García, A. (2019). Mechanical and Self-Healing Properties of Stone Mastic Asphalt Containing Encapsulated Rejuvenators. *Journal of Materials in Civil Engineering*, *31*, 1-10. https://doi.org/10.1061/(ASCE)MT.1943-5533.0002687

Ohama, Y. (1998). Polymer-based admixtures. *Cement and Concrete Composites*, *20*(2-3), 189-212.

Persoff, P., Apps, J., Moridis, G., & Whang, J. M. (1999). Effect of dilution and contaminants on sand grouted with colloidal silica. *Journal of Geotechnical and Geoenvironmental Engineering*, *125*(6), 461-469.

Petry, T. M., & Lee, T.-W. (1988). *Comparison of quicklime and hydrated lime slurries for stabilization of highly active clay soils*.

Prusinski, J. R., & Bhattacharja, S. (1999). Effectiveness of Portland cement and lime in stabilizing clay soils. *Transportation research record*, *1652*(1), 215-227.

Ramaji, A. E. (2012). A review on the soil stabilization using low-cost methods. *Journal of Applied Sciences Research*, *8*(4), 2193-2196.

Sherwood, P. (1993). *Soil stabilization with cement and lime*.

Skels, P., Bondars, K., & Korjakins, A. (2013). Unconfined compressive strength properties of cement stabilized peat. *CIVIL ENGINEERING'13*, 202.

Spagnoli, G. (2018). A review of soil improvement with non-conventional grouts. *International Journal of Geotechnical Engineering*, *15*(3), 273-287. https://doi.org/10.1080/19386362.2018.1484603

Tan, E., Zahran, E., & Tan, S. (2020). A review of chemical stabilisation in road construction. IOP Conference series: materials science and engineering, Timilsena, Y. P., Akanbi, T. O., Khalid, N., Adhikari, B., & Barrow, C. J. (2019). Complex coacervation: Principles, mechanisms and applications in microencapsulation. *International journal of biological macromolecules*, *121*, 1276-1286.

Tingle, J. S., Newman, J. K., Larson, S. L., Weiss, C. A., & Rushing, J. F. (2007). Stabilization mechanisms of nontraditional additives. *Transportation research record*, *1989*(1), 59-67.

Tsige, D., Korita, M., & Beyene, A. (2022). Deformation analysis of cement modified soft clay soil using finite element method (FEM). *Heliyon*, *8*(6), e09613. https://doi.org/https://doi.org/10.1016/j.heliyon.2022.e09613

Wang, J. Y., Soens, H., Verstraete, W., & De Belie, N. (2014). Self-healing concrete by use of microencapsulated bacterial spores. *Cement and Concrete Research*, *56*, 139-152. https://doi.org/10.1016/j.cemconres.2013.11.009

Wong, C., Pedrotti, M., El Mountassir, G., & Lunn, R. J. (2018). A study on the mechanical interaction between soil and colloidal silica gel for ground improvement. *Engineering Geology*, *243*, 84-100. https://doi.org/10.1016/j.enggeo.2018.06.011

Xu, D., Chen, W., & Fan, X. (2020). Experimental investigation of particle size effect on the self-healing performance of microcapsule for cemented coral sand. *Construction and Building Materials*, *256*, 119343. https://doi.org/https://doi.org/10.1016/j.conbuildmat.2020.119343

Zhu, D. Y., Rong, M. Z., & Zhang, M. Q. (2015). Self-healing polymeric materials based on microencapsulated healing agents: From design to preparation. *Progress in Polymer Science*, *49-50*, 175-220. https://doi.org/https://doi.org/10.1016/j.progpolymsci.2015.07.002

Zulkifley, M. T. M., Ng, T. F., Raj, J. K., Hashim, R., Bakar, A. F. A., Paramanthan, S., & Ashraf, M. A. (2014). A review of the stabilization of tropical lowland peats. *Bulletin of Engineering Geology and the Environment*, *73*(3), 733-746.

The paper was published in the proceedings of the 9th International Congress on Environmental Geotechnics (9ICEG), Volume 3, and was edited by Tugce Baser, Arvin Farid, Xunchang Fei and Dimitrios Zekkos. The conference was held from June 25th to June 28th 2023 in Chania, Crete, Greece.