Biological Stabilisers in Earthen Construction: A Mechanistic Understanding of their Response to Water-Ingress

Author(s):
Kulshreshtha, Yask; Vardon, Philip J.; Du, Yi; Habert, Guillaume; Vissac, Aurélie; Morel, Jean-Claude; Rao, Sudhakar M.; von Paassen, Leon; van Loosdrecht, Mark C.M.; Mota, Nelson J.A.; Jonkers, Henk M.

Publication date:
2022-01

Permanent link:
https://doi.org/10.3929/ethz-b-000516236

Originally published in:
Construction Technologies and Architecture 1, https://doi.org/10.4028/www.scientific.net/CTA.1.529

Construction Technologies and Architecture *Online: 2022-01-06*
ISSN: 2674-1237, Vol. 1, pp 529-539
doi:10.4028/www.scientific.net/CTA.1.529

Biological Stabilisers in Earthen Construction: A Mechanistic Understanding of their Response to Water-Ingress

Y. Kulshreshtha[1,a*], P.J. Vardon[1,b], Y. Du[2,c], G. Habert[2,d], A. Vissac[3,e], J.C. Morel[4,f], S.M. Rao[5,g], L. van Paassen[6,h], M.C.M. van Loosdrecht[7,i], N.J.A. Mota[8,j], H.M. Jonkers[1,k]

[1]Faculty of Civil Engineering and Geosciences, Delft University of Technology, The Netherlands

[2]Chair of Sustainable Construction, ETH Zurich, Switzerland

[3]Amaco-atelier matières à construire - Les Grands Ateliers, Villefontaine, France

[4]Faculty Research Centre for Built & Natural Environment, Coventry University, Coventry, UK

[5]Department of Civil Engineering, Indian Institute of Science, Bangalore, India

[6]Centre for Bio-mediated and Bio-inspired Geotechnics, Arizona State University, USA

[7]Faculty of Applied Sciences, Delft University of Technology, The Netherlands

[8]Faculty of Architecture and the Built Environment, Delft University of Technology, The Netherlands

[a*]Y.Kulshreshtha@tudelft.nl, [b]p.j.vardon@tudelft.nl, [c]du@ibi.baug.ethz.ch, [d]habert@ibi.baug.ethz.ch, [e]aurelie.vissac@amaco.org, [f]jeanclaude.frederick.morel@gmail.com, [g]msrao@iisc.ac.in, [h]leon.vanpaassen@asu.edu, [i]m.c.m.vanloosdrecht@tudelft.nl, [j]n.j.a.mota@tudelft.nl, [k]h.m.jonkers@tudelft.nl

*Corresponding author

Keywords: earthen construction, biological stabiliser, organic stabiliser, water ingress, water-resistance

Abstract. Earthen construction is re-gaining popularity as an ecological and economical alternative to contemporary building materials. While building with earth offers several benefits, its performance due to water ingress is a concern for its widespread application. This limitation is often solved by adding chemical stabilisers such as Portland cement and hydraulic lime. Chemical stabilisers are a subject of widespread debate as they increase the cost and embodied energy of the structure, and reduce the desirable characteristics of raw or unstabilised earth. This along with perceived environmental performance, renewability, and proven effectiveness in traditional earthen construction has led to a growing interest in biological or organic stabilisers. Although the strengthening mechanism of biological stabilisers is widely covered in scientific studies, discussion regarding the water-resistance is limited. This review aggregates the research from the field of earthen construction and geotechnical engineering and extends it to explain the possible mechanism responsible for the water-resistance behaviour of biologically stabilised earthen materials. This study includes a wide range of traditional and industrial biological stabilisers derived from animals (cow-dung, casein, chitosan), plants (starch, guar gum, cactus mucilage, lignin, tannin) seaweeds (alginate, agar, carrageen) and microbes (xanthan gum, gellan gum). A conceptual model of water-ingress in unstabilised earthen blocks is proposed and the response of biological stabiliser to water ingress and related physico-chemical and physical factors is discussed using the model at microscale (stabiliser interaction with clay, sand) and macroscale (hydraulic conductivity of block). Properties of stabilisers such as hydrophobicity, stability under wet conditions or interaction with cations have a dominant effect on the overall response to water ingress. Key gaps have been identified in the existing knowledge that are necessary to investigate in order to understand the water-resistance behaviour comprehensively. The study concludes with a brief assessment of biological stabilisers based on their performance and feasibility to use in contemporary earthen construction.

1 Introduction

The construction sector accounts for 36% of global energy use and 39% of energy and process-related carbon dioxide emissions (UN Environment and International Energy Agency, 2018). The high impact of the building sector has led to a growing interest in alternative building materials, such as earth (mud). Buildings made with earth are considered economical and ecological compared to houses built with concrete and fired bricks. As a building material, earth offers several advantages such as the improvement of the indoor air quality and thermal comfort, reduced operational and embodied energy use and have potential for reuse with the same embodied energy (Fabbri and Morel, 2016; Minke, 2006). However, concerns related to the mechanical and durability related performance of earthen structures are the key reason for its negative perception, especially in developing countries, therefore limiting its widespread use (Kulshreshtha et al., 2020).

While the strength of earthen material is sufficient for the construction of low-rise structures, its failure is often a result of low durability (Beckett et al., 2020). The durability of earthen structures is affected by environmental actions such as water ingress, or erosion due to wind, fire, solar radiation, growth of microorganisms and burrowing from animals (Fabbri et al., 2018; Laborel-Préneron et al., 2016). Amongst these actions, erosion due to water ingress has the highest impact on the performance of an earthen structure during its service life (Fabbri et al., 2018).

The technical limitations of earthen materials are often solved by the use of stabilisers or binders. The most common stabilisers used in contemporary earthen construction are Portland cement and hydraulic lime (often referred to as ‘chemical stabilisers’). The use of chemical stabilisers is subject to widespread debate as they increase the embodied energy and reduce moisture buffering capacity (capacity to regulate the indoor temperature and moisture) of earthen structures (Arrigoni et al., 2017; Treloar et al., 2001; Venkatarama Reddy and Prasanna Kumar, 2010). Moreover, they increase the cost and impact the reusability of earthen structures (Gallipoli et al., 2017). This debate has led to a growing interest in research in alternative and eco-friendly stabilisers (Fabbri and Morel, 2016; Şengör, 2019). In this regard, research into biological or organic stabilisers is on the rise mainly due to their perceived environmental performance, local availability, renewability of source, biodegradability (affecting re-use) and proven effectiveness in traditional earthen construction (Şengör, 2019; Vissac et al., 2017).

Although a few review studies have covered these stabilisers for their strengthening effect on soil (Chang et al., 2020; Jang, 2020), discussion regarding the durability aspects such as water-resistance is limited. Therefore, the present review aggregates studies from the field of earthen construction and geotechnical engineering and extends it to understand the response of biologically stabilised earthen materials to water-ingress. This study reviews a wide range of traditional and industrial biological stabilisers derived from animals (cow-dung, casein, chitosan), plants (starch, guar gum, cactus mucilage, lignin, tannin), seaweeds (alginate, agar, carrageen) and microbes (xanthan gum, gellan gum) with respect to their response to water ingress.

In the subsequent sections, the factors affecting water ingress in unstabilised earthen material and its disintegration are summarised and hence used in understanding the response of water ingress in biologically stabilised earthen material. Due to lack of fundamental studies on the water-resistance of earthen building materials, information was drawn from the field of unsaturated soil mechanics, in particular, studies on wetting-induced deformation relevant for landfill and embankment design. A maximum of two studies on each biological stabiliser is selected for this investigation. Biological stabilisers used in combination with other stabilisers are excluded.

2 Water Ingress in Unstabilised Earthen Materials

Water ingress in earthen materials can occur due to wind-driven rainfall, condensation, infiltration, absorption from the surrounding ground etc. (Beckett et al., 2020). In extreme cases (often experienced in the delta regions and river basins of developing countries), flooding can also lead to failure of earthen structures. Water ingress through immersion is used in this study to develop a conceptual model. This route is preferred because it is a commonly used laboratory test method and could be useful to assess stabiliser efficacy (Beckett et al., 2020).

The water-resistance of construction materials is often perceived as linked with strength properties. While these properties are inter-related, the factors affecting are not necessarily the same. The strength of unstabilised earthen material (such as rammed earth) is demonstrated to be dependent on the capillary suction between soil aggregates and is directly related to the dry density and the moisture content (relative humidity) in the sample (Bui et al., 2014; Jaquin et al., 2009). The capillary suction and strength increases with increasing dry density and decreasing moisture content.

The disintegration of earthen material, such as earthen blocks, upon water ingress, can be attributed to reduction in capillary suction that holds the aggregates together (Tadepalli and Fredlund, 1991). The rate of reduction in capillary suction is related to the ability of water to flow in the earthen material. The flow rate depends on the permeability or hydraulic conductivity of the soil and the hydraulic gradient. Permeability is linked to microstructural fabric (arrangement of particles and resulting pore size distribution and connectivity) and is influenced by the material’s largest pores (Leroueil and Hight, 2013). Compacted earthen material displays two types of pore space: inter-aggregate pores or macro-pores between solid aggregates and intra-aggregate pores or micro-pores between the individual particles within the aggregates (Romero, 2013). The macro-pores are known to be mainly responsible for water permeability (Romero, 2013). Therefore, reduction in macro-pore size can reduce the susceptibility of earthen material to water ingress. In parallel to the physical characteristics of microstructural fabric, the resistance to moisture ingress also depends on the soil’s vulnerability to the physico-chemical interaction between water molecules and soil surface (particularly in clays). The physico-chemical process includes the forces and energy responsible for adsorption and desorption of water molecules, thereby affecting the moisture retention and moisture transport in the earthen material. Therefore, the amount and activity of the clay minerals in the material have a significant influence on the water-resistance. The various factors affecting the microstructural fabric and hydraulic conductivity are illustrated and summarised in Fig.1. These factors are drawn from multiple studies (Choudhury and Bharat, 2018; Delage et al., 1996; Lawton et al., 1989; Leroueil and Hight, 2013; Lim and Miller, 2004; Watabe et al., 2000; Yesiller and Shackelford, 2011).

Apart from amount and type of clays, the compaction force and especially compaction water content (amount of water in soil during compaction) have a significant effect on the microstructural fabric and hydraulic conductivity. With an increase in compaction water content, especially beyond optimum moisture content (OMC), the water-resistance of earthen material was also found to increase. In an experimental study carried out by the first author (unpublished), the unstabilised samples prepared at higher water content could sustain immersion and drip erosion significantly better than samples prepared at water content lower than OMC (both samples were of same dry density).

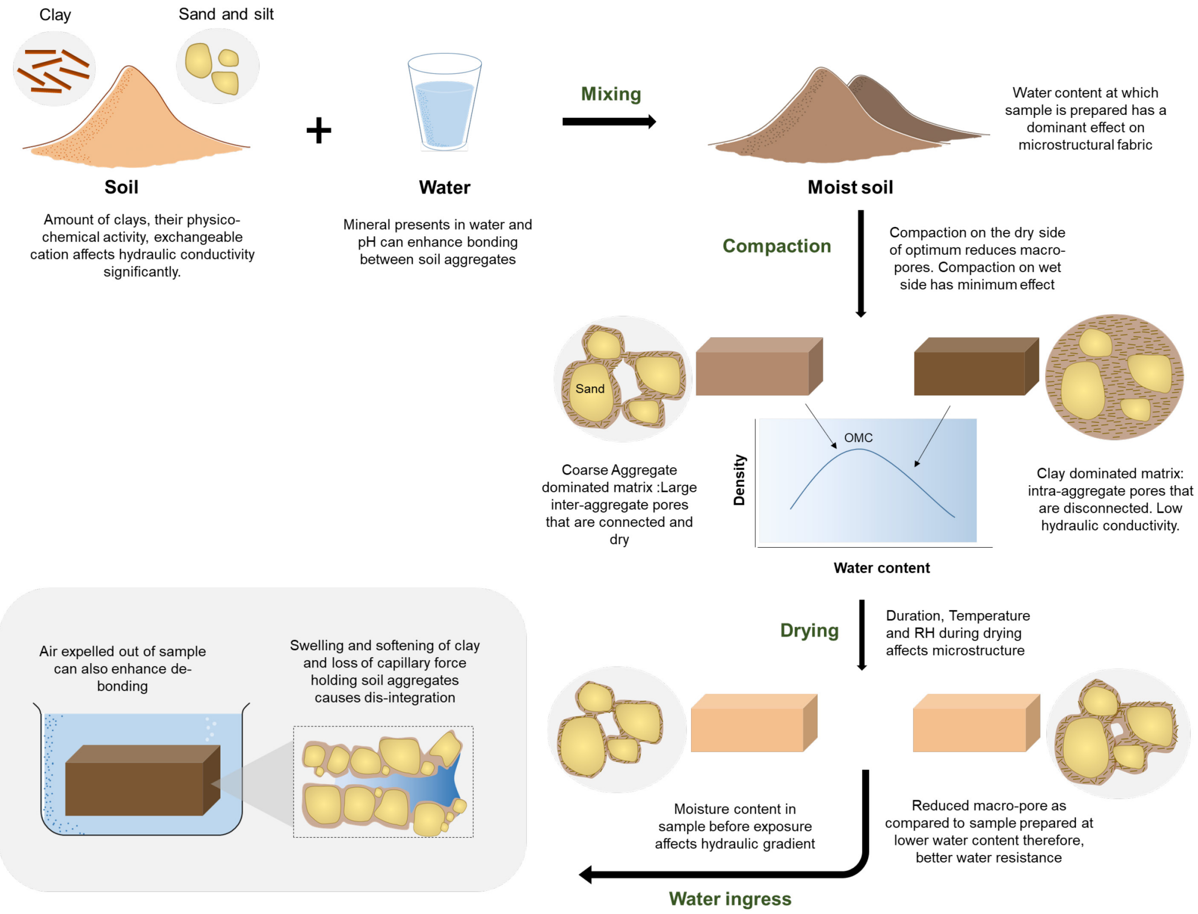

Fig. 1: Factors affecting the microstructure fabric and hydraulic conductivity of unstabilised earthen block. OMC refers to an optimum moisture content which corresponds to a maximum dry density

3 Response of Biological Stabilised Earthen Material to Water Ingress

The addition of biological stabilisers in earthen materials results in the modification of the microstructural fabric and physico-chemical interactions of the soil with water. The physical process of reducing macro-pore size through pore-filling is often proposed as a mechanism for the gain in strength and increase in water-resistance of biologically stabilised material (illustrated in fig. 2.). Biological stabilisers can swell when they interact with water, which can further reduce the pore size, however, they also begin to lose their stiffness, which results in weakening, allowing the soil to swell thereby giving further access to water. While the physical processes influence the hydraulic properties of the material, the physico-chemical interaction could be a dominant factor in improving the water-resistance of biologically stabilised earthen material. In this regard, the amount of clay particles, mineralogy and thereby activity can have a strong influence on the overall stability of material immersed in water. The ions and minerals present in water also play an essential role in the physico-chemical interaction. When a biological stabiliser is added to clayey soil, it can interact with soil aggregates, as shown in Fig. 2.

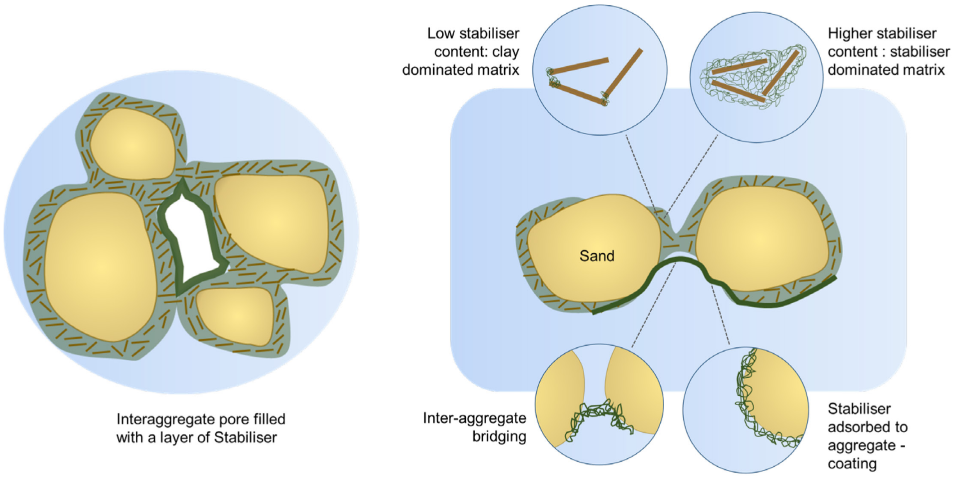

Fig. 2: Pore filling (left) and interaction various adsorption sites of biological stabiliser with aggregates (right)

The stabiliser content, the amount of water it is dissolved in, the clay content and clay mineralogy affect the extent of interaction between the different particles and resulting strength and water-ingress. Upon water-ingress in stabilised non-cohesive soils (sand), the interfacial properties of sand-stabiliser and the properties of the stabilisers would be responsible for resisting the moisture ingress. Disintegration could happen if and when the stabiliser starts solubilising with percolating water, reducing its capacity to hold the aggregates together. De-bonding of the stabiliser from the surface of sand could also be responsible for its dis-integration. In the case of compacted clayey soil, the inclusion of clay makes the system more complex. The clay particles, based on their amount and activity, can interact and form composites with the stabiliser. Clay particles have a negative charge on their surface, while edge charge depends on the pH or surrounding media. Due to availability of interaction sites, it can bond with the stabiliser through ionic interactions, hydrogen bonding, cation exchange or any other bonding mechanism. When the affinity between clay and stabiliser is low, the clay particles are known to be in a phase-separated state, where they are separated by the matrix of the stabiliser (Babu Valapa et al., 2017). This affinity depends on the clay mineral, and often with kaolinite mineral (most commonly used clay minerals in earthen construction), the affinity is low unless functional groups facilitating interaction are present in the stabiliser (Babu Valapa et al., 2017). When an earthen block is immersed in water, water moves through the macro-pores and interacts with the surrounding material of the pores. The biological stabiliser can affect the surface characteristics, like surface charge, hydrophobicity and cation exchange capacity, and consequently affect the physical-chemical interactions between liquid and solid phase. However, when the ions present in water start forming bonds with stabilisers, they can cause swelling and softening of stabiliser, and provide a route for water to interact with the clays. The swelling of clay can create micro-cracks in the matrix facilitating further movement of water. The softening or loss of stiffness of the matrix, coupled with reduced capillary suction due to the presence of water, results in separation of aggregates. Therefore, the interaction between the clay particles and the properties of stabilisers (which can be modified through heat and chemical treatment) plays a significant role in aggregate stability and water-resistance.

The interaction mechanisms reported in the literature for each stabiliser, including treatments for improved resistance, are explained briefly below. Most of these mechanisms are proposed for strengthening but could equally contribute towards water-resistance.

3.1 Stabilisers derived from animals

Cow-dung is a commonly used traditional stabiliser that improves the water-resistance of earthen materials; however, there is a lack of reserach focusing on the interaction mechanisms explaining its behaviour. Although formation of an insoluble compound formed by the reaction of amine compounds in cow-dung with fine quartz in soil under alkaline condition (pH 12) is proposed (Millogo et al., 2016), the unusual high alkaline condition of cow-dung is not common in nature. The role of extracellular polysaccharide secreting bacteria, as suggested in a recent study (Rao et al., 2020), could be explored to further understand the water-resistance of cow-dung.

Casein, a protein extracted from mammalian milk, is known to have both hydrophilic and hydrophobic groups (Horne, 2008). The hydrophilic groups are proposed to adsorb onto the clay while the hydrophobic groups are exposed to the environment, thus forming a surface that resists water ingress (Vissac et al., 2013). The performance of casein can be improved by treating it in an alkaline medium with cations and heating, facilitating edge ionic interaction with clays. Stabilisation with casein (6.6%) was shown to prevent disintegration of earthen block immersed in water for 24 hours, resulting in wet compressive strength of 0.75 MPa (Chang et al., 2018).

Chitosan is a polysaccharide obtained from (discarded) crab or shrimps shells. The water-resistant properties of chitosan can be linked to its hydrophobicity (Aguilar et al., 2016) and electrostatic interaction between positively charged chitosan with negatively charged clay (Hataf et al., 2018). Chitosan-coated earthen samples (0.5-3%) were seen to pass the 10 min limit of drip erosion test whereas, uncoated samples disintegrated in 1 minute (Aguilar et al., 2016). The contact angle of 140° was measured for chitosan-coated sand particles showing the hydrophobicity (Donayre et al., 2018)

3.2 Stabilisers derived from plants

Starch, a polysaccharide extracted from plant and vegetable, is known to adsorb onto clay through hydrogen bonding (Husband, 1998). However, starch stabilisation is enahnced when it is heated during or after mixing. The heat-induced transformation of starch results in the formation of a gel matrix that binds the soil aggregates together. The extent of gelatinisation affects water-resistance behaviour. Sand stabilised with completely gelatinised starch (16.7%) can survive up to 7 days of immersion in water (Kulshreshtha et al., 2017).

Guar gum, a polysaccharide extracted from seeds of guar plant, forms hydrogel film over soil aggregates and results in pore filling. The use of guar gum has proven to lower hydraulic conductivity (Bouazza et al., 2009). Studies on guar gum stabilised earthen materials have shown a 2-3 times improvement in water-resistance measured through drip erosion test and dry and wet cycles (Muguda et al., 2020; Sujatha and Saisree, 2019).

Cactus mucilage is a traditional stabiliser known to improve the surface texture of stabilised soil through pore-filling (Akinwumi and Ukegbu, 2015). Stabilisation with cactus mucilage has shown up to 25 times improvement in water resistance during wetting and drying test (Heredia Zavoni et al., 1988).

Lignin is a by-product of paper and bioethanol industry that has been extensively studied. Lignin consists of hydrophilic and hydrophobic groups and improves water-resistance through various proposed mechanisms such as pore filling, ionic interaction and cation exchange (Zhang et al., 2020). Soil stabilised with a lignin rich product (12%) resisted 7 days of immersion without disintegration (Yang et al., 2018).

Tannin, extracted from bark, leaves, seeds and other parts of some trees, has been used as a stabiliser in traditional earthen construction for its water-resistance properties. There is a lack of research on water-resistance, and only one dataset from Banakinao et al. (2016) showed evidence of improved water-resistance of tannin stabilised earthen blocks. In the study on strength properties, the formation of tannin-iron complex due to polymersation or oxidation of tannin into an insoluble substance was reported to improve strength (Keita et al., 2014), and thus could also be the reason for increased water-resistance.

3.3 Stabilisers derived from Seaweed

Alginate, a polysaccharide extracted from brown seaweed, is gaining popularity in the field earthen construction due to gelation properties at room temperature. Sodium alginate is soluble in water, but when exposed to a calcium-rich environment, it forms an insoluble gel. Sand stabilised with alginate

(0.4%), exposed to $CaCl_2$ solution could survive 12 cycles of wetting and drying, where each cycle consisted of 24h of immersion (Wen et al., 2019).

Agar gum, extracted from marine red algae, is known to form a network after cooling from elevated temperature (cold-set gelation) (Burey et al., 2008). Agar mixed with hot water before stabilising the clayey soil and sand, resulted in the sample resisting immersion for up to 7 days (Chang et al., 2015). The wet strength was assumed to be governed by the behaviour of agar gel in water and pore-filling.

Carrageenan, extracted from red seaweed, is a stabiliser that requires comprehensive study into its water-resistance mechanism. Carrageenan coated clayey soil proved to be effective against water erosion and the material passed 10-minute drip erosion test as compared to unstabilised soil that failed in 5 minutes. Moreover, the contact angle of coated samples was measured in the range of 101°-104°, proving to be hydrophobic (Nakamatsu et al., 2017).

3.4 Stabilisers derived from Microbes

Xanthan gum, extracted from bacteria found on cabbage plants, has been extensively studied for improvement of strength and durability properties of soils and earthen materials. The formation of thick gel via hydrogen bonding coats the soil particles and results in pore filling (Chen et al., 2019). Stablised sand (2%) resisted multiple drying and wetting cycles (Qureshi et al., 2017), whereas in clayey soil (3%) the mass loss in the drip erosion test was 2% as compared to 7.5% in the unstabilised sample (Muguda et al., 2020).

Gellan gum is known to stabilise soil through pore filling, particle coating, and hydrogel matrices (Chang et al., 2015). A stabilised clayey soil (3% gellan gum) and sand (1%) stabilised survived the 7-day water immersion.

A summary of the interaction mechanism proposed by various studies is illustrated in Fig 3. It can be inferred that the native or modified properties of stabilisers themselves could improve water-resistance of stabilised material significantly (as shown in the studies related to non-cohesive particles such as sand). However, the possibility to form ionic bonds and affect the cation exchange of clays can improve the properties further. Hydrogen bonding is a commonly proposed reaction mechanism with clays (and sand) which is weaker than ionic bonding and cation exchange and is sensitive to ions presents in the water.

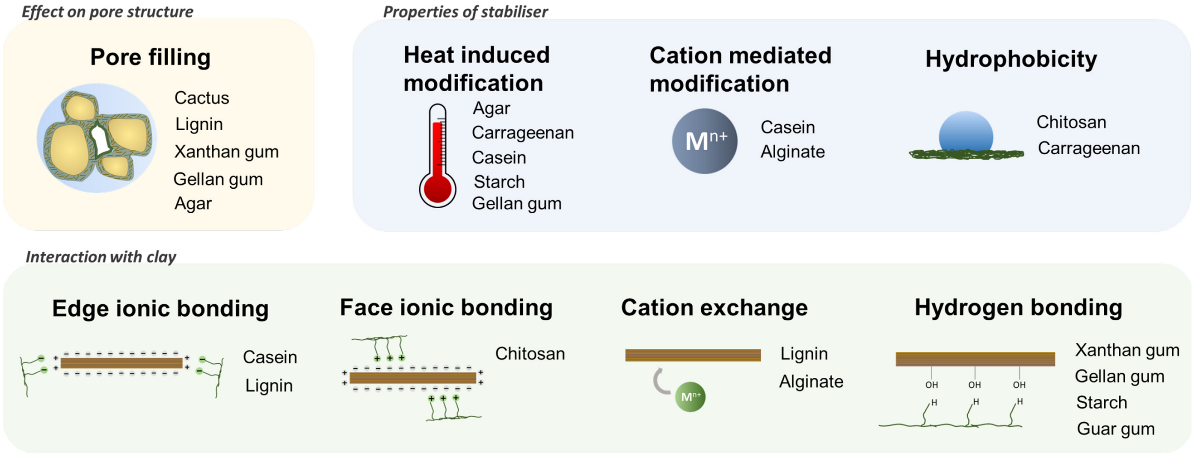

Fig. 3: Proposed Interaction mechanism facilitating water-resistance of biologically stabilised earthen material

4 Research Gaps and Assessment of Biological Stabiliser

Most research on biological stabilisation so far has focused on strength development, whereas it is known that earthen structures usually fails due to durability related aspects. There is a lack of good quality research focused on water-resistance of biologically stabilised earthen materials. Moreover, studies looking into a mechanistic understanding of water-resistance are absent, except in a few stabilisers such as lignin. Specific attention is required on the research on traditional stabilisers such as cow-dung, cactus and tannins. These stabilisers are still used in rural areas of developing countries, and comprehensive research could benefit several earthen house dwellers. While the potential of chitosan and carrageenan is explored in some studies, more research is required on the water resistance properties of these stabilisers. Fundamental studies on understanding the response to water ingress in unstabilised earthen materials are also needed.

Some studies on biological stabilisers have shown significant improvement in strength compared to cement stabilised earthen material (Chang et al., 2020). However, biological stabilisers have not been able to perform as well in durability tests. The cost and local availability of the stabilisers are also important criteria affecting the application of a specific stabiliser. At present, the costs of biological stabilisers are significantly higher than cement and hydraulic lime, even though lower quantities of the material are required for stabilisation. Moreover, while biological stabilisers are perceived environmental friendly, a clear assessment through life cycle analysis is required to reveal their ecological impact. Extraction of industrial biological stabilisers involves chemical processing and heat-treatment, which can increase their ecological cost. In this regard, stabilisers that can be extracted from waste (such as cow-dung, casein, chitosan, starch) could be explored further as alternative stabilisers. To assess the overall performance of biologically stabilised earthen material, a fair comparison should be made with unstabilised and cement/lime stabilised earthen material on parameters such as durability, strength, environmental friendliness, moisture buffering behaviour, recyclability, long term field performance, bio-degradation, availability, acceptability and economy.

5 Acknowledgement

The authors would like to acknowledge Coralie Brumaud for her feedback on the article.

References

[1] Aguilar, R., Nakamatsu, J., Ramírez, E., Elgegren, M., Ayarza, J., Kim, S., Pando, M.A., Ortega-San-Martin, L., 2016. The potential use of chitosan as a biopolymer additive for enhanced mechanical properties and water resistance of earthen construction. Constr. Build. Mater. 114. https://doi.org/10.1016/j.conbuildmat.2016.03.218

[2] Akinwumi, I.I., Ukegbu, I., 2015. Soil modification by addition of cactus mucilage. Geomech. Eng. 8, 649–661. https://doi.org/10.12989/gae.2015.8.5.649

[3] Arrigoni, A., Grillet, A.-C., Pelosato, R., Dotelli, G., Beckett, C.T.S., Woloszyn, M., Ciancio, D., 2017. Reduction of rammed earth's hygroscopic performance under stabilisation: an experimental investigation. Build. Environ. 115, 358–367. https://doi.org/10.1016/j.buildenv.2017.01.034

[4] Babu Valapa, R., Loganathan, S., Pugazhenthi, G., Thomas, S., Varghese, T.O., 2017. An Overview of Polymer–Clay Nanocomposites, in: Clay-Polymer Nanocomposites. Elsevier, pp. 29–81. https://doi.org/10.1016/B978-0-323-46153-5.00002-1

[5] Banakinao, S., Tiem, S., Lolo, K., Koutsawa, Y., Bedja, K.-S., 2016. Dataset of the use of tannin of néré (parkia-biglobosa) as a solution for the sustainability of the soil constructions in West Africa. Data Br. 8, 474–483. https://doi.org/10.1016/j.dib.2016.05.072

[6] Beckett, C.T.S., Jaquin, P.A., Morel, J.-C., 2020. Weathering the storm: A framework to assess the resistance of earthen structures to water damage. Constr. Build. Mater. 242, 118098. https://doi.org/10.1016/j.conbuildmat.2020.118098

[7] Bouazza, A., Gates, W.P., Ranjith, P.G., 2009. Hydraulic conductivity of biopolymer-treated silty sand. Géotechnique 59, 71–72. https://doi.org/10.1680/geot.2007.00137

[8] Bui, Q.-B., Morel, J.-C., Hans, S., Walker, P., 2014. Effect of moisture content on the mechanical characteristics of rammed earth. Constr. Build. Mater. 54, 163–169. https://doi.org/10.1016/j.conbuildmat.2013.12.067

[9] Burey, P., Bhandari, B.R., Howes, T., Gidley, M.J., 2008. Hydrocolloid Gel Particles: Formation, Characterization, and Application. Crit. Rev. Food Sci. Nutr. 48, 361–377. https://doi.org/10.1080/10408390701347801

[10] Chang, I., Im, J., Chung, M.-K., Cho, G.-C., 2018. Bovine casein as a new soil strengthening binder from diary wastes. Constr. Build. Mater. 160, 1–9. https://doi.org/10.1016/j.conbuildmat.2017.11.009

[11] Chang, I., Lee, M., Tran, A.T.P., Lee, S., Kwon, Y.-M., Im, J., Cho, G.-C., 2020. Review on biopolymer-based soil treatment (BPST) technology in geotechnical engineering practices. Transp. Geotech. 24, 100385. https://doi.org/10.1016/j.trgeo.2020.100385

[12] Chang, I., Prasidhi, A.K., Im, J., Cho, G.-C., 2015. Soil strengthening using thermo-gelation biopolymers. Constr. Build. Mater. 77, 430–438. https://doi.org/10.1016/J.CONBUILDMAT.2014.12.116

[13] Chen, C., Wu, L., Perdjon, M., Huang, X., Peng, Y., 2019. The drying effect on xanthan gum biopolymer treated sandy soil shear strength. Constr. Build. Mater. 197, 271–279. https://doi.org/10.1016/j.conbuildmat.2018.11.120

[14] Choudhury, C., Bharat, T.V., 2018. Wetting-induced collapse behavior of kaolinite: influence of fabric and inundation pressure. Can. Geotech. J. 55, 956–967. https://doi.org/10.1139/cgj-2017-0297

[15] Delage, P., Audiguier, M., Cui, Y.-J., Howat, M.D., 1996. Microstructure of a compacted silt. Can. Geotech. J. 33, 150–158. https://doi.org/10.1139/t96-030

[16] Donayre, A., Sanchez, L.F., Kim, S., Aguilar, R., Nakamatsu, J., 2018. Eco-friendly Improvement of Water Erosion Resistance of Unstable Soils with Biodegradable Polymers. IOP Conf. Ser. Mater. Sci. Eng. 416, 012044. https://doi.org/10.1088/1757-899X/416/1/012044

[17] Fabbri, A., Morel, J.-C., Gallipoli, D., 2018. Assessing the performance of earth building materials: a review of recent developments. RILEM Tech. Lett. 3, 46–58. https://doi.org/10.21809/rilemtechlett.2018.71

[18] Fabbri, A., Morel, J.C., 2016. Earthen materials and constructions, in: Nonconventional and Vernacular Construction Materials. Elsevier, pp. 273–299. https://doi.org/10.1016/B978-0-08-100038-0.00010-X

[19] Gallipoli, D., Bruno, A.W., Perlot, C., Mendes, J., 2017. A geotechnical perspective of raw earth building. Acta Geotech. 12, 463–478. https://doi.org/10.1007/s11440-016-0521-1

[20] Hataf, N., Ghadir, P., Ranjbar, N., 2018. Investigation of soil stabilization using chitosan biopolymer. J. Clean. Prod. 170, 1493–1500. https://doi.org/10.1016/j.jclepro.2017.09.256

[21] Heredia Zavoni, E.A., Bariola Bernales, J.J., Neumann, J.V., Mehta, P.K., 1988. Improving the moisture resistance of adobe structures. Mater. Struct. 21, 213–221. https://doi.org/10.1007/BF02473058

[22] Horne, D.S., 2008. Casein micelle structure and stability, in: Milk Proteins. Elsevier, pp. 133–162. https://doi.org/10.1016/B978-0-12-374039-7.00005-2

[23] Husband, J.C., 1998. The adsorption of starch derivatives onto kaolin. Colloids Surfaces A Physicochem. Eng. Asp. 131, 145–159. https://doi.org/10.1016/S0927-7757(96)03881-2

[24] Jang, J., 2020. A Review of the Application of Biopolymers on Geotechnical Engineering and the Strengthening Mechanisms between Typical Biopolymers and Soils. Adv. Mater. Sci. Eng. 2020, 1–16. https://doi.org/10.1155/2020/1465709

[25] Jaquin, P.A., Augarde, C.E., Gallipoli, D., Toll, D.G., 2009. The strength of unstabilised rammed earth materials. Géotechnique 59, 487–490. https://doi.org/10.1680/geot.2007.00129

[26] Keita, I., Sorgho, B., Dembele, C., Plea, M., Zerbo, L., Guel, B., Ouedraogo, R., Gomina, M., Blanchart, P., 2014. Ageing of clay and clay–tannin geomaterials for building. Constr. Build. Mater. 61, 114–119. https://doi.org/10.1016/j.conbuildmat.2014.03.005

[27] Kulshreshtha, Y., Mota, N.J.A., Jagadish, K.S., Bredenoord, J., Vardon, P.J., van Loosdrecht, M.C.M., Jonkers, H.M., 2020. The potential and current status of earthen material for low-cost housing in rural India. Constr. Build. Mater. 247, 118615. https://doi.org/10.1016/j.conbuildmat.2020.118615

[28] Kulshreshtha, Y., Schlangen, E., Jonkers, H.M., Vardon, P.J., van Paassen, L.A., 2017. CoRncrete: A corn starch based building material. Constr. Build. Mater. 154, 411–423. https://doi.org/10.1016/j.conbuildmat.2017.07.184

[29] Laborel-Préneron, A., Aubert, J.E., Magniont, C., Tribout, C., Bertron, A., 2016. Plant aggregates and fibers in earth construction materials: A review. Constr. Build. Mater. 111, 719–734. https://doi.org/10.1016/j.conbuildmat.2016.02.119

[30] Lawton, E.C., Fragaszy, R.J., Hardcastle, J.H., 1989. Collapse of Compacted Clayey Sand. J. Geotech. Eng. 115, 1252–1267. https://doi.org/10.1061/(ASCE)0733-9410(1989)115:9(1252)

[31] Leroueil, S., Hight, D., 2013. Compacted soils: From physics to hydraulic and mechanical behaviour, in: Advances in Unsaturated Soils. CRC Press, pp. 41–59. https://doi.org/10.1201/b14393-6

[32] Lim, Y.Y., Miller, G.A., 2004. Wetting-Induced Compression of Compacted Oklahoma Soils. J. Geotech. Geoenvironmental Eng. 130, 1014–1023. https://doi.org/10.1061/(ASCE)1090-0241(2004)130:10(1014)

[33] Millogo, Y., Aubert, J.-E., Séré, A.D., Fabbri, A., Morel, J.-C., 2016. Earth blocks stabilized by cow-dung. Mater. Struct. 49, 4583–4594. https://doi.org/10.1617/s11527-016-0808-6

[34] Minke, G., 2006. Building with Earth, Design and technology of a sustainable architecture. Birkhäuser Basel, Basel. https://doi.org/10.1007/3-7643-7873-5

[35] Muguda, S., Lucas, G., Hughes, P.N., Augarde, C.E., Perlot, C., Bruno, A.W., Gallipoli, D., 2020. Durability and hygroscopic behaviour of biopolymer stabilised earthen construction materials. Constr. Build. Mater. 259, 119725. https://doi.org/10.1016/j.conbuildmat.2020.119725

[36] Nakamatsu, J., Kim, S., Ayarza, J., Ramírez, E., Elgegren, M., Aguilar, R., 2017. Eco-friendly modification of earthen construction with carrageenan: Water durability and mechanical assessment. Constr. Build. Mater. 139, 193–202. https://doi.org/10.1016/j.conbuildmat.2017.02.062

[37] Qureshi, M.U., Chang, I., Al-Sadarani, K., 2017. Strength and durability characteristics of biopolymer-treated desert sand. Geomech. Eng. 12, 785–801. https://doi.org/10.12989/gae.2017.12.5.785

[38] Rao, S.M., Sukumar, R., Joshua, R.E., Mogili, N.V., 2020. Biocementation of soft soil by carbonate precipitate and polymeric saccharide secretion. Bioinspired, Biomim. Nanobiomaterials 9, 241–251. https://doi.org/10.1680/jbibn.20.00032

[39] Romero, E., 2013. A microstructural insight into compacted clayey soils and their hydraulic properties. Eng. Geol. 165, 3–19. https://doi.org/10.1016/j.enggeo.2013.05.024

[40] Şengör, S.S., 2019. Review of Current Applications of Microbial Biopolymers in Soil and Future Perspectives. pp. 275–299. https://doi.org/10.1021/bk-2019-1323.ch013

[41] Sujatha, E.R., Saisree, S., 2019. Geotechnical behaviour of guar gum-treated soil. Soils Found. 59, 2155–2166. https://doi.org/10.1016/j.sandf.2019.11.012

[42] Tadepalli, R., Fredlund, D.G., 1991. The collapse behavior of a compacted soil during inundation. Can. Geotech. J. 28, 477–488. https://doi.org/10.1139/t91-065

[43] Treloar, G.J., Owen, C., Fay, R., 2001. Environmental assessment of rammed earth construction systems. Struct. Surv. 19, 99–106. https://doi.org/10.1108/02630800110393680

[44] UN Environment and International Energy Agency, 2018. Towards a zero-emission, efficient, and resilient buildings and construction sector. Global Status Report 2018.

[45] Venkatarama Reddy, B.V., Prasanna Kumar, P., 2010. Embodied energy in cement stabilised rammed earth walls. Energy Build. 42, 380–385. https://doi.org/10.1016/j.enbuild.2009.10.005

[46] Vissac, A., Bourgès, A., Gandreau, D., Anger, R., Fontain, L., 2017. Argiles & Biopolymères. CRAterre, Villefontaine.

[47] Vissac, A., Couvreur, L., Moevus, M., 2013. Tâche 5 PaTerre + PNRCC.

[48] Watabe, Y., Leroueil, S., Le Bihan, J.-P., 2000. Influence of compaction conditions on pore-size distribution and saturated hydraulic conductivity of a glacial till. Can. Geotech. J. 37, 1184–1194. https://doi.org/10.1139/t00-053

[49] Wen, K., Li, Y., Huang, W., Armwood, C., Amini, F., Li, L., 2019. Mechanical behaviors of hydrogel-impregnated sand. Constr. Build. Mater. 207, 174–180. https://doi.org/10.1016/j.conbuildmat.2019.02.141

[50] Yang, B., Zhang, Y., Ceylan, H., Kim, S., Gopalakrishnan, K., 2018. Assessment of soils stabilized with lignin-based byproducts. Transp. Geotech. 17, 122–132. https://doi.org/10.1016/j.trgeo.2018.10.005

[51] Yesiller, N., Shackelford, C.D., 2011. Geoenvironmental Engineering, in: Das, B.M. (Ed.), Geotechnical Engineering Handbook. J. Ross Publishing, Inc.

[52] Zhang, T., Yang, Y.-L., Liu, S.-Y., 2020. Application of biomass by-product lignin stabilized soils as sustainable Geomaterials: A review. Sci. Total Environ. 728, 138830. https://doi.org/10.1016/j.scitotenv.2020.138830

The publication of this article was funded by the Delft University of Technology 10.13039/501100001831