S.M. Viswanath, S.J. Booth, P.N. Hughes, C.E. Augarde, C.Perlot, A.W. Bruno, D. Gallipoli (2017).

Mechanical properties of biopolymer-stabilised soil-based construction materials.

Géotechnique Letters, 7(4): 1–18

http://dx.doi.org/10.1680/jgele.17.00081

- Date text written: 01-11-17
- Number of words in your main text and tables, followed by the number of figures: 2363 words, 2 Tables and 5 Figures

---

Mechanical properties of biopolymer-stabilised soil-based construction materials

Author 1

- Sravan Muguda
- Department of Engineering, Durham University, Durham, UK & Laboratoire SIAME, Fédération IPRA, Université de Pau et des Pays de l'Adour, Anglet, France
- Orcid Number : 0000-0003-3108-5716

Author 2

- Samuel John Booth
- (formerly) Department of Engineering, Durham University, Durham, UK

Author 3

- Dr Paul Neil Hughes
- Department of Engineering, Durham University, Durham, UK
- Orcid Number : 0000-0002-7260-794X

Author 4

- Prof. Charles Edward Augarde
- Department of Engineering, Durham University, Durham, UK

- Orcid Number : 0000-0002-5576-7853

Author 5
- Dr Celine Perlot
- Laboratoire SIAME, Fédération IPRA, Université de Pau et des Pays de l'Adour, Anglet, France

Author 6
- Dr Agostino Walter Bruno
- Laboratoire SIAME, Fédération IPRA, Université de Pau et des Pays de l'Adour, Anglet, France
- Orcid Number : 0000-0002-1408-4132

Author 7
- Prof. Domenico Gallipoli
- Laboratoire SIAME, Fédération IPRA, Université de Pau et des Pays de l'Adour, Anglet, France
- Orcid Number : 0000-0003-1576-0742

Full contact details of corresponding author.
Sravan Muguda Viswanath

Marie Curie Early Stage Researcher

Department of Engineering, Durham University, Durham, DH1 3LE, UK & Laboratoire SIAME, Fédération IPRA, Université de Pau et des Pays de l'Adour, Anglet, France

Email id: sravan.muguda-viswanath@durham.ac.uk

Abstract (200 words)

Soil-based construction materials are of interest as structural building materials due to their green credentials, as well as being present in many historical structures. For effective conservation of the latter, and to motivate greater uptake for new construction, understanding of the mechanical and hydraulic properties of these materials is in need of improvement. Earthen construction materials can be considered to be manufactured unsaturated soils, and advances in understanding can be made by considering them from a geotechnical point of view. This paper presents initial results from a major programme of testing, seeking improved properties for earthen construction materials, where unusual organic compounds have been employed as stabilisers. Two gums (guar and xanthan) used as stabilisers for a soil mixture are shown to have significant effects on certain mechanical properties, some of which can be explained, and other aspects which are in need of further investigation.

Keywords chosen from ICE Publishing list

Suction; Partial saturation; Laboratory tests;

List of notations

OWC	Optimum water content
$\gamma_{d,max}$	Maximum dry density
RH	Relative Humidity

Introduction

Earthen construction refers to the use of subsoil materials to create structural members, such as walls, and is distinguished from other forms of construction that use soils (e.g. earth dams) by the difference in environment, i.e. large surfaces open to the weather and consequently low water content. Techniques are both unit-based (e.g. adobe and compressed earth blocks) and in-situ (e.g. rammed earth, pisé and cob). These methods of construction have been used by man for thousands of years and are coming under scrutiny for modern construction as they could offer low carbon and low embodied energy alternatives to construction using cement-based products or fired masonry (Jaquin & Augarde, 2012). It is only in the last decade, however, that these materials have been correctly identified as geotechnical in nature, i.e. where frictional strength is key and unsaturated soil mechanics concepts are useful (Jaquin *et al.*, 2009; Gallipoli *et al.*, 2014, 2017; Beckett *et al.*, 2017). A key barrier to wider adoption of these materials for modern construction, especially in temperate zones such as northern Europe, is their poorly understood mechanical properties. Modern earthen materials often use stabilisers such as cement to provide bonding, but this clashes with their green credentials and alternative stabilisers are therefore keenly sought.

Biopolymers are naturally occurring polymers, typically from plant sources, which have been previously used as viscosifiers (Plank, 2004). Recently, researchers have explored the possibility of using biopolymers as soil stabilisers, and it has been reported that, when added to soil biopolymers have reduced soil permeability (Bouazza *et al.*, 2009; Aminpour & O'Kelly, 2015), increased shear strength (Cabalar & Canakci, 2011; Chang *et al.*, 2015), improved compressibility (Latifi *et al.*, 2016) and enhanced durability (Qureshi *et al.*, 2017). Biopolymer stabilisation changes soils properties by the formation through hydration of “hydrogels”. On drying, the water molecules tend to escape from polymer chains leading to the formation of complexes of linked polymer chains. In addition, during drying, the hydrogels transform from what is termed a “rubbery” to a “glassy” state (Eichler *et al.*, 1997; Ayeldeen *et al.*, 2016). When mixed in soil, the hydrogels form bonds between soil particles and free water through hydrogen and/or ionic bonding depending on the intrinsic properties of the biopolymer used (Chudzikowski, 1971; Katzbauer, 1998). From the findings in these previous works, it is clear that biopolymers may have potential as stabilisers in soil-based construction materials, providing additional shear strength and stiffness, without the carbon footprint of a cement stabiliser. Indeed the production of xanthan gum actually consumes CO_2 (Chang *et al.*, 2016). This paper presents initial results from a campaign of laboratory testing assessing the mechanical properties of biopolymer-treated materials, and speculates on potential explanations.

2. Experimental Programme

A base soil mixture comprising 20% Kaolin, 70% sharp sand and 10% gravel by mass (denoted 2-7-1) was chosen as it complies with the requirements for earthen construction materials given in previous publications (Olivier & Mesbah, 1987; Houben & Guillaud, 1994; Venkatarama Reddy & Jagadish, 1995; Beckett & Augarde, 2012) and is a combination widely investigated. Atterberg limits and compaction characteristics (using the 2.5kg Proctor test) obtained in accordance with British Standards (BS 1377-2, 1990; BS 1377-4, 1990) for the unamended soil mixture are given in Table 1. Commercially available guar gum and xanthan gum were chosen as biopolymer stabilisers in this study due to their availability and good stability properties with respect to temperature and pH variations (Mudgil *et al.*, 2011). As indicated in literature when added within a range of 3.0%, the biopolymer treated soil has comparable performance with 10% cement treated soil (Chang *et al.*, 2015; Qureshi *et al.*, 2017), hence the biopolymer content in study was added in range of 0.5 to 3.0% by mass of the dry unamended sample.

Cylindrical specimens (38mm diameter by 76mm height) were tested in unconfined compression (UC), and “bowtie” specimens were tested in tension using the procedure outlined in Stirling *et al.* (2015). All the ingredients (the base soil mix and biopolymer) were dry mixed initially and then water equivalent to OWC was added. During preparation of treated samples, it was necessary to add additional water above the OWC in order to make the soil mix workable. The amount of additional water required varied with respect to the biopolymer used and can be explained by the different chemical compositions of the gums as discussed in (Torres *et al.*, 2012) wherein the polymer chains in guar have a lower water absorption capacity than in xanthan, and therefore need more water to hydrate and hence achieve a workable soil mix. The amounts of additional water needed for both biopolymers are given in Table 2. All the samples were statically compacted to achieve the initial dry density of 19.62 kN/m^3 having a porosity of 16.98% and pore void volume of 14.63 cm^3. However, due to the addition of biopolymer there was slight variation in the initial dry densities achieved and corresponding porosity and pore space volume values. Following preparation, samples were left to cure by drying to the laboratory atmosphere (relative humidity of 50% and temperature of 21^{0}C) and were then tested after 7 and 28 days. Finally, water content and total suction (using a WP4C Potentiometer) were measured on portions of the remains. For comparison, identical tests were carried out on samples of the unamended soil after 7 days of air curing and on samples stabilised with 8.0% cement by mass after 7 and 28 days of air curing. Similarly to biopolymer-stabilised samples, air curing took place inside the laboratory atmosphere.

3. Results and Discussion

Axial stress/strain plots recorded during the UC tests are shown in Figure 1. The differences in stiffness at low axial strains are due to sample bedding in and the key conclusions should be drawn from the results > 0.5% strain. After 7 days of curing, for both guar and xanthan treated specimens, there is an appreciable difference in the > 0.5% stiffness between different concentrations, with higher concentrations leading to higher stiffness. At 28 days curing, however, these differences are no longer evident. These variations of the stiffness provide evidence of the change of state of the hydrogel products formed by the biopolymers, which is discussed in more detail below.

UC peak strength is plotted against % stabiliser in Figure 2 for both biopolymers, where it can be seen that an addition of 2% guar provides soil with compressive strength higher than the cement-stabilised sample: approximately 30% higher after 7 days and 35% after 28 days. After 7 days, xanthan at 1.5% produces approximately the same strength as the cement stabilised specimen and, at 2%, the strength becomes approximately 50% higher than the cement stabilised specimens. However, xanthan specimens tested at 28 days showed reductions in strength compared to the 7 day specimens. For the range of percentage stabiliser additions, both plots show increasing strength, with no optimum treatment concentration reached within the range tested, although all treated samples improve on the unamended soil. Given the variation in strength behaviour between stabiliser concentrations and curing periods discussed above the primary mechanisms controlling strength would appear to be different to that driving stiffness.

Tensile test results are shown in Figure 3 indicating a clear relationship between stabiliser concentration and tensile strength. The error bars show the greater variation for these tests which can be explained by the different modes of failure. Tensile strength will be critically affected by the presence and nature of microcracking which will vary between samples and be difficult to predict or control. Shear failure in the UC tests show much less scatter as the resistance to failure is more distributed over a surface. Unlike the UC results, the tensile strength of the guar samples reduces over time whereas the xanthan samples increase over time. At 7 days, all concentrations of biopolymer lead to higher tensile strengths than unamended soil, but lower than for the cement treated soil. At 28 days, the strength of the 2% xanthan gum treated soil exceeds the cement treated soil by 38%. Differences in the relative performances of cement and biopolymer treated samples when tested in tension, as opposed to compression, suggest that the stabilising mechanisms through which compressive and tensile resistance is mobilised within the specimens are different.

As noted in Jaquin *et al.* (2009), a significant component of the strength of unstabilised soil-based construction materials can be linked to the suction present due to the very low in-situ water contents and presence of fine soil fractions. Zhao (2014) and Cao *et al.,* (2017) using Tempe cell measured soil water characteristic curves (SWCCs) for poorly graded sand initially saturated with water and biopolymer solutions. It was noted higher matric suction was needed to desaturate sand treated with xanthan solution at 2g/L concentration, indicating that addition of biopolymer will have an effect on suction of treated soil (Fig 4). In addition, Chang *et al* (2015b) note that the strength of the biopolymer stabilised soil is dependent on water content, although that point is not relevant to this study where the end application is a material dried to the environmental equilibrium. It is therefore instructive to measure suction for the materials tested here to try to understand the effect of biopolymer addition on suction and potentially strength.

Figure 5 shows suction and water content data recorded immediately after UC strength testing. Some observations are as follows:

- All biopolymer treated samples exhibit higher suctions than the unamended and cement treated specimens indicating a contribution from osmotic suction from biopolymer products (indeed suctions are evident in samples of plain hydrated biopolymer confirming this). The effect is not dependent on % stabiliser at 28 days but at 7 days there is a variation indicating that as the hydrogels change state, their contribution to suction varies.
- At 28 days, the water content of guar gum treated samples was higher than 7 days, while for xanthan treated samples it was lesser. This variation may be due to their interaction with surrounding atmosphere. As noted by Kocherbitov *et al.,* (2010), the vapour sorption/diffusion of a biopolymer is dependent on its state, temperature and humidity. Hence, by end of 28 days, guar gum stabilises through water absorption from atmosphere, while xanthan gum, uses as much free water as it needs, with the remainder of the water evaporating.
- At 7 days, the suction measured in the unamended samples corresponds to the value calculated using Kelvin's equation, given the average RH and temperature in the laboratory. For the amended samples, however, suction equilibrates at a higher level, between 125 and 135 MPa, further confirming osmotic suction contributions from the presence of the biopolymer products.
- Water contents increase with % stabiliser throughout which is linked to the additional water required to achieve workable mixes
- After 7 days, high suctions are linked to low water contents for both gums indicating a more significant contribution to suction from pore water than at 28 days.

When the suction results are reviewed in parallel with the UC strength data (Figure 2) clear conflicts are evident. For the guar samples, suctions are seen to reduce between 7 and 28 days, while UC strengths increase. Equally, for the xanthan samples, suctions increase while UC strengths decrease. Changes in UC strength must therefore be explained through additional mechanisms besides suction induced capillary bonding. Conversely, suction changes shown in Figure 5 correspond well with changes in tensile strength of the biopolymer treated soils in that decreases in suction of guar gum samples after 28 days correspond to lower strengths, and increases in suction in xanthan gum samples correspond to higher strengths. The higher suctions and strengths of the biopolymer treated specimens compared to the untreated specimens suggest that the strength gains are caused by a combination of suction (mainly osmotic) and hydrogel bonding. The nature of the bonding of these hydrogels with soil particles depends on the biopolymer type.

Guar gum, being a neutrally charged polysaccharide with large hydroxyl groups (Chudzikowski, 1971), forms a network of hydrogels between soil particles and free water via hydrogen bonds (Chen *et al.*, 2013). At 7 days, these hydrogels (predominantly being in rubbery state) may contribute to matric suction and hence the stabiliser content contributes to the measured suction (Figure 5). Thereby, the combination of suction and hydrogels contribute to the observed higher compressive strength of the soil. Tensile strength is also believed to be driven by a combination of suction and hydrogel bonding. However, as hydrogels are more elastic and weaker than cement bonds in tension, the tensile strengths are lower than the cement treated specimens. Once the hydrogels transform to a glassy state, the suctions tend to reduce and reach constant values irrespective of stabiliser content (Fig. 5). However, the increase in compressive strength and stiffness may be attributed to the network of hydrogels now in a glassy state connecting the soil particles. Being a weaker chemical bond, the hydrogen bonds may not contribute to tensile strength with aging.

Xanthan gum is an anionic polysaccharide (Katzbauer, 1998; Garcıa-Ochoa *et al.*, 2000) and the gum may interact with cations of the clay portion of the soil mix to form chemically stronger ionic bonds in addition to hydrogen bonds (Chang *et al.*, 2015a). This combination of ionic and hydrogen bonds will result in better aggregation of the soil particles (Chen *et al.*, 2013). Similar to guar gum, at 7 days, the combination of suction and hydrogel bonding contributes to both compressive and tensile behaviour of xanthan treated soils. Whilst there is a slight decrease in compressive strength at 28 days, ionic bonding and transformation of hydrogels is reflected in higher suction which in turn results in higher stiffness (Fig. 1) and increases in tensile strength with time for xanthan treated soils.

4. Conclusions

The initial results presented here appear to show that significant improvements to the mechanical properties of soil-based construction materials can be obtained using guar and xanthan gum biopolymers as stabilisers. General trends are explained and areas of contradiction highlighted. Additional investigation is ongoing, to determine the nature of the bonding in the treated soils.

Acknowledgements

We acknowledge the support of the European Commission via the Marie Skłodowska-Curie Innovative Training Networks (ITN-ETN) project TERRE 'Training Engineers and Researchers to Rethink geotechnical Engineering for a low carbon future’ (H2020-MSCA-ITN-2015-675762).

References

Aminpour, M. & O’Kelly, B. C. (2015). Applications of biopolymers in dam construction and operation activities, in Pina C., Portela E., Caldeira L., Batista A., D. I. and S. R. (ed.) *Proceedings of the Second International Dam World Conference (DW2015)*. Lisbon, Portugal: LNEC, 937–946.

Ayeldeen, M. K., Negm, A. M. & El Sawwaf, M. A. (2016). Evaluating the physical characteristics of biopolymer/soil mixtures, *Arabian Journal of Geosciences*, **9**(**5**), 10.1007/s12517-016-2366-1.

Beckett, C. & Augarde, C. (2012). The effect of humidity and temperature on the compressive strength of rammed earth, in *Unsaturated Soils: Research and Applications*. Berlin, Heidelberg: Springer Berlin Heidelberg, 287–292.

Beckett, C. T. S., Augarde, C. E., Easton, D. & Easton, T. (2017). Strength characterisation of soil-based construction materials., *Géotechnique.* Thomas Telford.

Bouazza, A., Gates, W. P. & Ranjith, P. G. (2009). Hydraulic conductivity of biopolymer-treated silty sand, *Géotechnique*, **59**(**1**), 71–72, 10.1680/geot.2007.00137.

BS 1377-2 (1990). *Methods of test for Soils for civil engineering purposes - Part 2 : Classification tests*, *BSI*. London.

BS 1377-4 (1990). *Methods of test for Soils for civil engineering purposes - Part 4 : Compaction* *tests*, *BSI*. London.

Cabalar, A. F. & Canakci, H. (2011). Direct shear tests on sand treated with xanthan gum, *Proceedings of the ICE - Ground Improvement*, **164**, 57–64, 10.1680/grim.800041.

Cao, J., Jung, J., Song, X. & Bate, B. (2017). On the soil water characteristic curves of poorly graded granular materials in aqueous polymer solutions, *Acta Geotechnica*. Springer Berlin Heidelberg, 10.1007/s11440-017-0568-7.

Chang, I., Im, J. & Cho, G.-C. (2016). Introduction of Microbial Biopolymers in Soil Treatment for Future Environmentally-Friendly and Sustainable Geotechnical Engineering, *Sustainability*, **8**(**3**), 251, 10.3390/su8030251.

Chang, I., Im, J., Prasidhi, A. K. & Cho, G.-C. (2015). Effects of Xanthan gum biopolymer on soil strengthening, *Construction and Building Materials*, **74**(**10**), 65–72, 10.1016/j.conbuildmat.2014.10.026.

Chang, I., Jeon, M. & Cho, G. (2015). Application of Microbial Biopolymers as an Alternative Construction Binder for Earth Buildings in Underdeveloped Countries, *International Journal of Polymer Science*, **2015**, 1–9, 10.1155/2015/326745.

Chang, I., Prasidhi, A. K., Im, J. & Cho, G.-C. (2015). Soil strengthening using thermo-gelation biopolymers, *Construction and Building Materials*, **77**(**2015**), 430–438, 10.1016/j.conbuildmat.2014.12.116.

Chen, R., Zhang, L. & Budhu, M. (2013). Biopolymer Stabilization of Mine Tailings, *Journal of Geotechnical and Geoenvironmental Engineering*, **139**(**10**), 1802–1807, 10.1061/(ASCE)GT.1943-5606.0000902.

Chudzikowski, R. J. (1971). Guar gum and its applications, *Journal of the Society of Cosmetic Chemists*. Citeseer, **22**(**1**), 43–60, 10.1016/j.ijbiomac.2016.04.001.

Eichler, S., Ramon, O., Ladyzhinski, I., Cohen, Y. & Mizrahi, S. (1997). Collapse processes in shrinkage of hydrophilic gels during dehydration, *Food Research International*, **30**(**9**), 719–726, 10.1016/S0963-9969(98)00028-3.

Gallipoli, D., Bruno, A. W., Perlot, C. & Mendes, J. (2017). A geotechnical perspective of raw earth building, *Acta Geotechnica*, 10.1007/s11440-016-0521-1.

Gallipoli, D., Bruno, A. W., Perlot, C. & Salmon, N. (2014). *Raw earth construction: is there a role for unsaturated soil mechanics*. Taylor & Francis Group, London, UK.

Garcıa-Ochoa, F., Santos, V. E., Casas, J. A. & Gomez, E. (2000). Xanthan gum: production, recovery, and properties, *Biotechnology advances*. Elsevier, **18**(**7**), 549–579.

Houben, H. & Guillaud, H. (1994). *Earth construction: a comprehensive guide*. Intermediate Technology Publications.

Jaquin, P. A., Augarde, C. E., Gallipoli, D. & Toll, D. G. (2009). The strength of unstabilised rammed earth materials, *Géotechnique*, **59**(**5**), 487–490, 10.1680/geot.2007.00129.

Jaquin, P. & Augarde, C. (2012). *Earth building: history, science and conservation*. Bracknell: IHS BRE Press.

Katzbauer, B. (1998). Properties and applications of xanthan gum, *Polymer Degradation and Stability*, **59**(**1**–**3**), 81–84, 10.1016/S0141-3910(97)00180-8.

Kocherbitov, V., Ulvenlund, S., Briggner, L.-E., Kober, M. & Arnebrant, T. (2010). Hydration of a natural polyelectrolyte xanthan gum: Comparison with non-ionic carbohydrates, *Carbohydrate Polymers*, **82**(**2**), 284–290, 10.1016/j.carbpol.2010.04.055.

Latifi, N., Horpibulsuk, S., Meehan, C. L., Abd Majid, M. Z., Tahir, M. M. & Mohamad, E. T. (2016). Improvement of Problematic Soils with Biopolymer—An Environmentally Friendly Soil Stabilizer, *Journal of Materials in Civil Engineering*, **29**(**2**), 10.1061/(ASCE)MT.1943-5533.0001706.

Mudgil, D., Barak, S. & Khatkar, B. S. (2011). Guar gum: processing, properties and food applications—A Review, *Journal of Food Science and Technology*, **51**(**6**), 409–418, 10.1007/s13197-011-0522-x.

Olivier, M. & Mesbah, A. (1987). Influence of different parameters on the resistance of earth, used as a building material, in *International Conference on Mud Architecture, Trivandrum, India*.

Plank, J. (2004). Applications of biopolymers and other biotechnological products in building materials, *Applied Microbiology and Biotechnology*, **66**(**1**), 1–9, 10.1007/s00253-004-1714-3.

Qureshi, M. U., Chang, I. & Al-Sadarani, K. (2017). Strength and durability characteristics of biopolymer-treated desert sand, *Geomechanics and Engineering,* **12(5)**, 785–801, 10.12989/gae.2017.12.5.785.

Stirling, R. A., Hughes, P., Davie, C. T. & Glendinning, S. (2015). Tensile behaviour of unsaturated compacted clay soils - A direct assessment method, *Applied Clay Science*. Elsevier B.V., **112**–**113**, 123–133, 10.1016/j.clay.2015.04.011.

Torres, M. D., Moreira, R., Chenlo, F. & Vázquez, M. J. (2012). Water adsorption isotherms of carboxymethyl cellulose, guar, locust bean, tragacanth and xanthan gums, *Carbohydrate polymers*. Elsevier, **89**(**2**), 592–598.

Venkatarama Reddy, B. V. & Jagadish, K. S. (1995). Influence of soil composition on the strength and durability of soil-cement blocks, *Indian Concrete Journal*, 517–524.

Zhao, X. (2014). Measurements and transient multistep outflow simulation of soil-water characteristic curve for soils modified with biopolymers. Missouri University of Science and Technology.

FIGURES

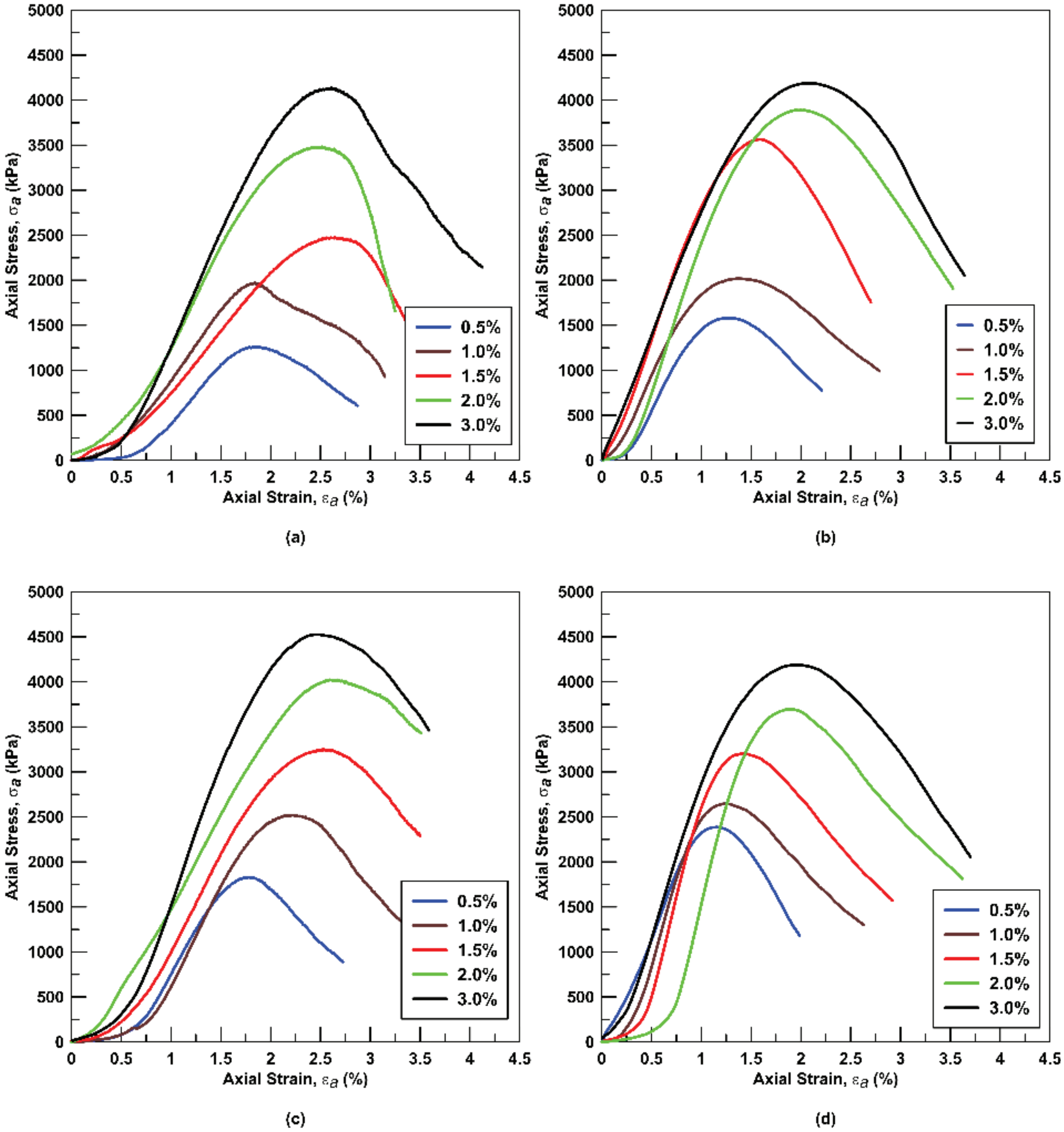
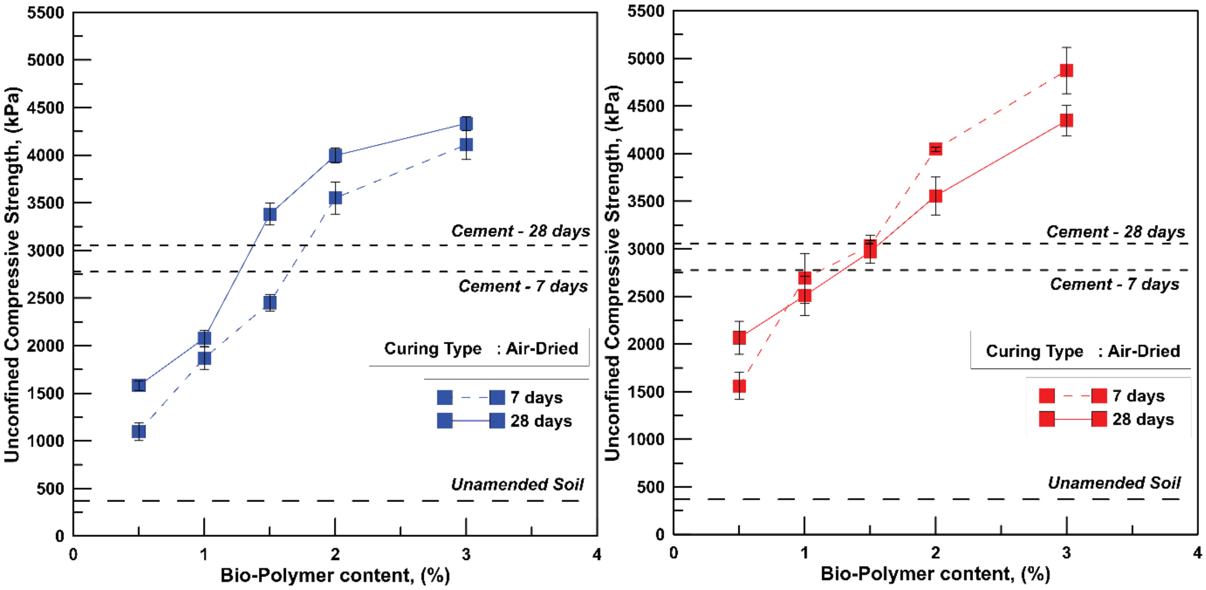
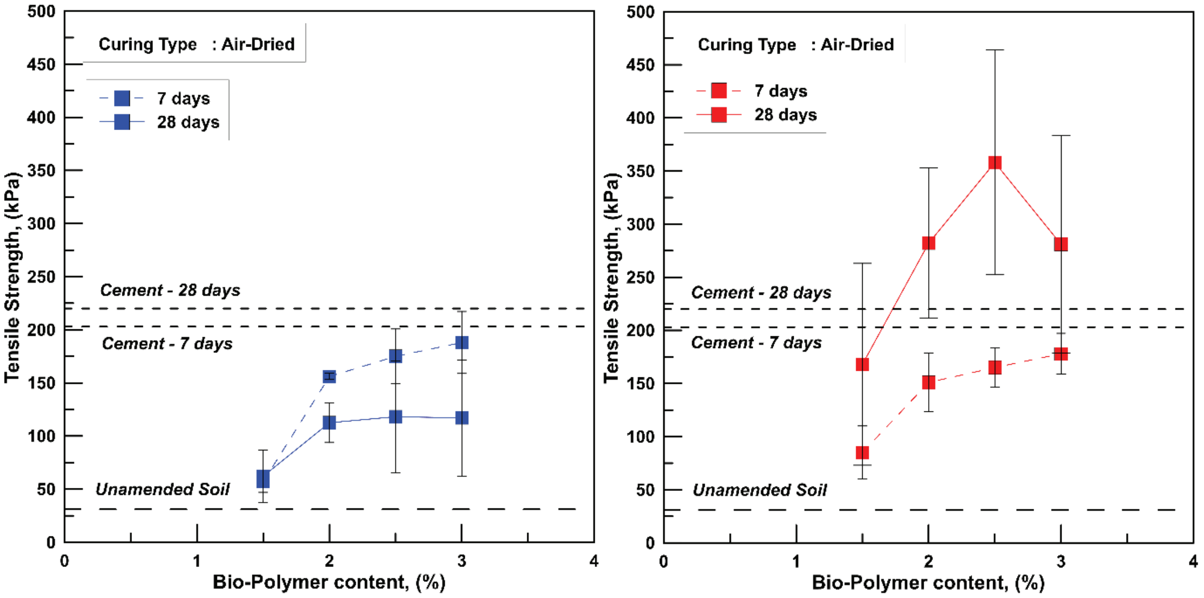


Figure 1: Stress-strain behaviour in UC tests (for each % stabiliser only one test among three replicates is shown): (a) guar gum, 7 days, (b) guar gum, 28 days, (c) xanthan gum, 7 days, (d) xanthan gum, 28 days



(a) (b)

Figure 2: UC test results (average values of peak strength based on three replicates), (a) guar gum, (b) xanthan gum.



(a) (b)

Figure 3. Tensile test results (average values of tensile strength based on three replicates), (a) guar gum, (b) xanthan gum.

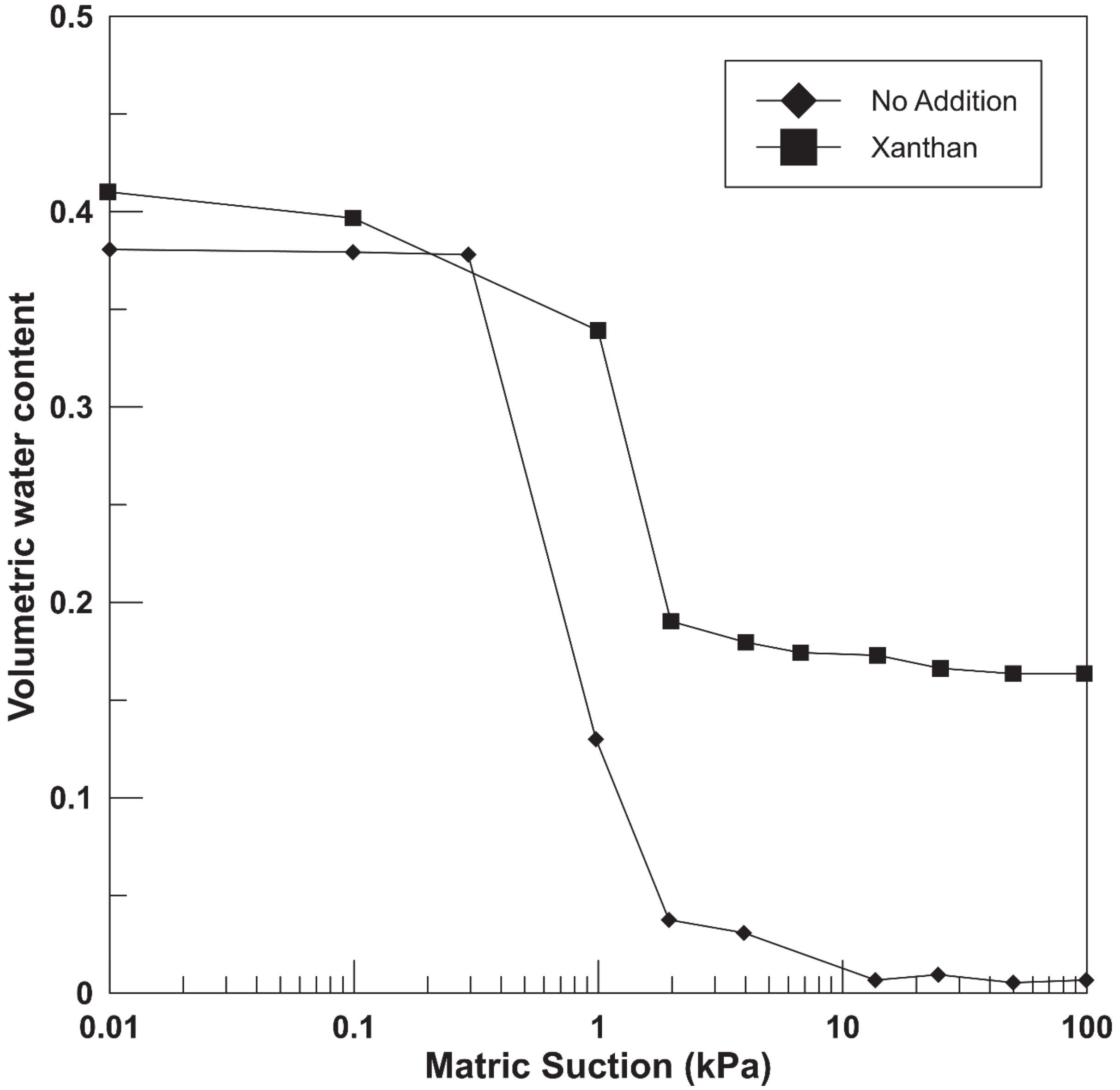
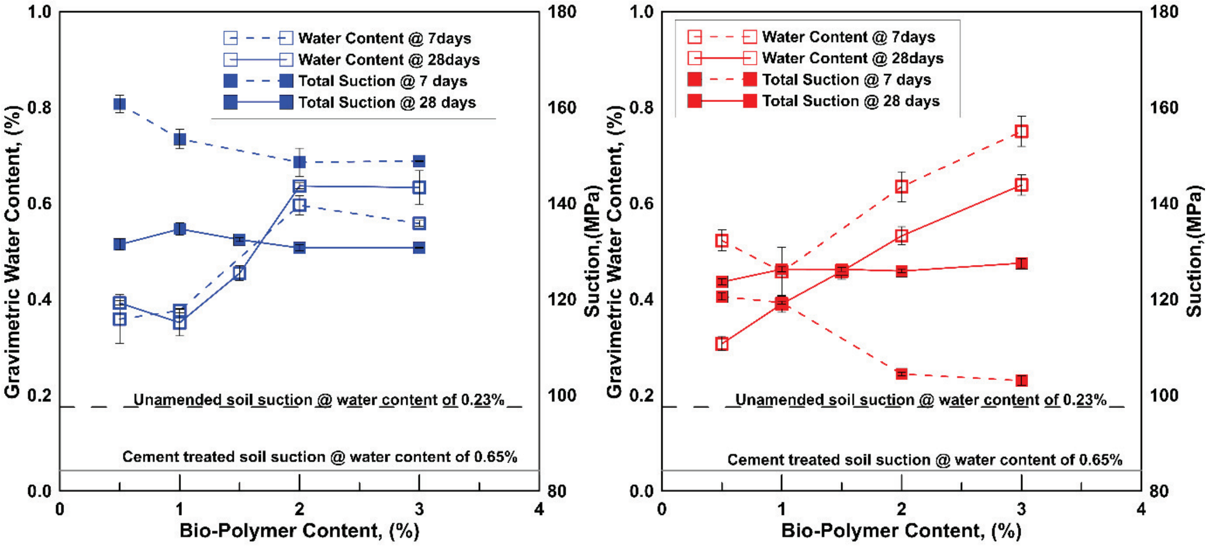


Figure 4. Changes in suction due to polymer treatment. (after Zhao, 2014)



(a) (b)

Figure 5. Suction and water content values at ends of UC tests (a) guar gum, (b) xanthan gum.

TABLES

Table 1: Physical properties of the unstabilised soil mixture used in this study

Soil	Clay (%)	Silt (%)	Sand (%)	Gravel (%)	Liquid Limit (%)	Plastic Limit (%)	OWC (%)	$\gamma_{d,max}$ (kN/m^3)
2-7-1	16	04	70	10	36.2	18.4	9.8	19.62

Table 2 : Amount of additional water needed for different biopolymer contents

Sl.No	Biopolymer content	Additional water added above OWC (%)	
		guar gum	xanthan gum
1	0.50	0.50	0.25
2	1.00	1.00	0.50
3	1.50	1.50	0.75
4	2.00	2.00	1.00
5	3.00	3.00	1.50