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Exploring the effect of biopolymers in near-surface soils using xanthan gum-modified sand under shear

Chunhui Chen; Li Wu; Michael Harbottle*

Chunhui Chen: China University of Geosciences Wuhan, Faculty of Engineering, No. 388 Lumo Road, Wuhan, P.R. China Postcode: 430074. Cardiff School of Engineering, Cardiff University, Queen's Buildings, The Parade, Cardiff, CF24 3AA, Wales, UK. Email: cchmike@hotmail.com

Li Wu: China University of Geosciences Wuhan, Faculty of Engineering, No. 388 Lumo Road, Wuhan, P.R. China Postcode: 430074. Email: lwu@cug.edu.cn

Michael Harbottle: * Corresponding author (Email: harbottlem@cardiff.ac.uk; Tel: +44 2920875759; Fax: +44 2920874716). Cardiff School of Engineering, Cardiff University, Queen's Buildings, The Parade, Cardiff, CF24 3AA, Wales, UK.

Abstract:

Biopolymers produced in near-surface soils by living organisms, including microbial extracellular polymeric substances and plant mucilage, offer enhanced moisture retention and protection from dry environments, lubricate roots to allow penetration through soil and link soil grains together physically to form soil aggregates. At the aggregate scale their effects and behaviour are known and significant but their impact on geotechnical behaviour of shallow soil bodies at the mesoscale and beyond is largely unexplored, including their response to the moisture cycling typical in vadose zone soils. In this work we explore the effects of moisture conditions, including multiple dry/wet cycles, on the shear behaviour of sand amended with xanthan gum as a model biopolymer. Drying causes a significant improvement on shear strength, even at low concentrations of biopolymer, but this is largely lost upon wetting. The extent of shear strength improvement is dependent on the moisture path taken (i.e. the wetting/drying history) and deteriorates over a number of moisture cycles. We present a conceptual model that poses redistribution of the biopolymer around the sand grains as the cause of the observed behaviour, and demonstrate that biopolymers can provide a significant although transient enhancement of shear strength of sand in near-surface conditions.

Keywords: extracellular polymeric substances, biopolymer, sand, direct shear

Introduction

Living organisms present in soil exude a range of biopolymers to help them overcome or adapt to environmental challenges (Brax et al. 2017; Hall-Stoodley et al. 2004). Such biopolymers are concentrated in the surface and near surface regions, where microorganisms are most numerous and plant roots and associated fungi and other microorganisms enmesh soil to form the rhizosphere (Burmølle et al. 2011). These biopolymers interact with soil particles to cause a stabilising effect in the soil, contributing to phenomena such as aggregation of particles and alteration to moisture regimes and flow patterns which impact upon the mechanical behaviour of surface soils (Brax et al. 2017; Chen et al. 2019).

Microorganisms produce extracellular polymeric substances (EPS) in the formation of biofilms, which can provide protection from issues such as predation, desiccation and adverse chemical environments. Biofilm assemblages are generally associated with grain surfaces, and may bridge two or more grains (Malam Issa et al. 2007) causing aggregation of grains and amending shear behaviour in sands (Banagan et al. 2010). Although additional cohesion appears to cause significant improvement in shear strength, it is expected that this phenomenon is restricted to near-surface soils, where a low effective stress acting on the soil skeleton allows a small cohesion to dominate, whereas at depth, frictional effects will dominate and little or no effect of the biopolymer will be observed, as noted by Perkins et al. (2000). Plant roots exude mucilage, a viscous biopolymer, which helps lubricate root tips and facilitates growth through the soil, but as it ages can form strong bonds between soil grains (Chen et al. 2019). This contributes to soil adhesion to the root, forming a rhizosheath (Albalasmeh and Ghezzehei 2014) whilst also causing grain aggregation in close proximity to the root (Erktan et al. 2017; Vezzani et al. 2018) – for example the addition of mucilage has been found to result in an increase in aggregation of 40% (Morel et al. 1991).

Such effects are enhanced by the dense population of microorganisms, and associated biopolymer production, present in the rhizosphere, supported by plant exudates including mucilage.

Biopolymers associated with both microorganisms and plants are readily biodegradable but are produced on a near continuous basis and so whilst there is considerable turnover there is overall a reasonably consistent level of total biopolymer present with values suggested overall of 0.02 to 1.4 mg per g dry soil (Chenu 1995), with mucilage contributing an estimated 0.05-50 mg per g dry soil (Zickenrott et al. 2016).

Under dry conditions, mucilage can retain water in the soil to help protect roots against desiccation, giving a much higher water content in the rhizosphere compared to the bulk soil (Carminati et al. 2010). Similarly, EPS in biofilm is capable of retaining moisture as protection against desiccation for its inhabitants. The properties of both mucilage and biofilm are hugely influenced by their moisture content and thus the moisture availability in the soil. Both swell and contract substantially as moisture availability increases and decreases and the polymers hydrate and dry (Brax et al. 2017). The mechanical behaviour of biopolymers is greatly affected by this hydration, as with swelling individual molecules interact less with each other whilst with drying interactions increase, secondary bonding increases and the viscosity of the biopolymer gel, and therefore its ability to resist mechanical forces, is greatly enhanced (Wassen et al. 2014). However, moisture changes within the biopolymer mass can be buffered as, for example, changes in biofilm structure as moisture levels change can counteract the effects of the external environment, particularly as the surface adopts a more ‘closed’ structure upon drying, limiting further moisture loss. The impact of biopolymers on soil geotechnical properties is therefore expected to be affected by changes in moisture availability. Moisture changes can be beneficial, however, causing EPS molecules to become more mobile in moist conditions and allowing a degree of diffusion away from the original source, increasing the interaction of biopolymer molecules with grain surfaces and thus enhancing binding effects (Mager and Thomas 2011).

The contribution of typical levels of biopolymer in soil to the geotechnical behaviour of the medium has been explored using a highly controlled artificial sand/biopolymer composite to model natural conditions. This enables the isolation of the effect of biopolymers specifically from other confounding factors, and allows us to determine the potential for natural biopolymers to be managed to enhance or control soil properties. Previously, relatively high levels of biopolymer additives have been considered as a ground improvement agent, with considerable impacts on the mechanical properties of the medium (Cabalar et al. 2018; Chang et al. 2016). However, the behaviour and contribution of lower levels of biopolymer, corresponding to those observed naturally in surface soils, is unknown. The purpose of this study was therefore to use artificial biopolymer to mimic natural biopolymers in the soil, and explore its influence on soil strength under different moisture conditions and moisture paths. A range of moisture conditions including drying, partial wetting, full submersion and drying-wetting cycles were applied to mimic realistic moisture regimes in the soil and to help understand the behaviour of soil/biopolymer composites under natural conditions.

Material and methods

Experimental materials

A fine to medium well graded silica sand was employed with properties as described in Table 1. The study used a non-cohesive soil in order to isolate the cohesive effects of biopolymers on the behaviour of a purely frictional material more clearly. Sand was dried at 105ºC prior to sample preparation.

The model biopolymer used in this study was xanthan gum, a commercial agent used in food production and rheology modification produced from *Xanthomonas campestris*. It has previously been found to be an acceptable model of both EPS (Czarnes et al. 2000; Malarkey et al. 2015) and plant mucilage (Di Marsico et al. 2018).

Sample preparation

All specimens were prepared within shear box apparatus constructed from Acetal copolymer, designed for applications at low normal stress due to its low density and coefficient of friction, ensuring that the effect of the box on shear stress is minimised. The two halves of these boxes were machined from single blocks of the material with no fixings or adhesives employed in their construction.

Dry sand (200 g per shear box) was mixed with xanthan gum gel (40 g per shear box) produced by mixing dry xanthan gum powder with deionised water on a magnetic stirrer for 120 minutes. Two different concentrations of gel (0.5 and 2.5% w/w) were prepared to give dry biopolymer concentrations of 0.1 and 0.5% of the dry sand mass. This corresponds to 1 and 5 mg dry polymer per g dry sand, within the typical ranges quoted for biopolymers in soil given previously. The sand/biopolymer composite was then placed in the shear box and compacted by hand tamping to produce an initial dry density ranging from 1587 kg/m^3 to 1603 kg/m^3 (void ratio between 0.65 and 0.67). The moisture content of 20% allowed for a homogenous final structure, and corresponds to a saturation ratio between 79 and 81% although the moisture is initially bound within the gel rather than being available to form menisci between sand grains.

Multiple samples were prepared in an identical manner and subjected to a range of changes to moisture levels. All moisture paths were tested with three identical replicates to confirm variability within the treatments. The moisture paths taken are described in Table 2, and explore the behaviour of sand/biopolymer composites subjected to a range of wetting and drying cycles describing in an idealised fashion the varying exposure of natural soils and biopolymers to moisture. It was hypothesised that changes in the response of the composite to loading would help to explain the changing nature and distribution of the biopolymer and its interaction with the sand. Four individual treatments were carried out, with the following methodologies:

- Full drying of samples took place in an oven at 40ºC until samples reached constant weight.
- Submerged samples were fully immersed in deionised water at room temperature for 24 hours such that the water level was level with the top of the sand. The aim was to achieve as near to saturation conditions as possible; Chang et al. (2016) achieved full saturation within 6 hours with an identical method although as different conditions (coarser sand

and higher gum content) were used it is not certain that complete saturation was achieved in this case.

- Dry samples were returned to the original moisture condition by placing samples in small-volume plastic bags (to minimise evaporation losses) before replenishing them with approximately 10 g deionised water per day until the original mass was restored.
- Submerged samples were returned to the original condition by drying at 40ºC as above until achievement of its original mass, at which point the sample was placed in a small-volume plastic bag for 24 hours to allow equilibration).

Direct shear tests

The effect of biopolymer on the mechanical behaviour of sand was determined using direct shear tests following the British Standard method (British Standard 1377-7: 1990), with adaptations as follows. All tests were performed on a Wykeham Farrance direct shear testing apparatus using shear boxes constructed from Acetal plastic, as discussed above, with low levels of normal stress (1, 10 and 30 kPa) applied using a hanger system apart from at very low stress (1 kPa) where the weight of the top cap was sufficient. The strain rate was 0.8 mm/min – previous studies using direct shear on gum-treated sands (Chang et al. 2016; Lee et al. 2017) employed a rate of 1-1.2 mm/min, with substantially higher gum contents. However, the sand used in this study was finer than that used here and so we employed a reduced rate to account for this.

Results and analysis

Biopolymer effect after drying or wetting

The initial impacts of wetting and drying on the shear behaviour of sand/biopolymer composites at low normal stresses are presented in Figure 1 and in general exhibit typical Mohr–Coulomb failure behaviour, with Mohr-Coulomb parameters from this data presented in Table 3. Very good experimental repeatability was observed, apart from dried specimens with both 0.1 and 0.5% biopolymer present where some variability between replicates is noted. The small apparent cohesion values may have arisen in part due to small operational errors, but cannot be attributed to moisture as they were observed even in dried sand without biopolymer. It is apparent that there is little to no effect of fresh biopolymer at either of the levels used on either cohesion or peak angle of friction. Similarly, submersion of the specimens led to no obvious distinction with or without different levels of biopolymer, although a small reduction in both cohesion and peak angle of friction was observed compared to the original state. It is possible that this was caused by small pore pressures developing in submerged specimens only, indicating that the testing rate used may have been slightly faster than desired for these specimens. The consistency of this effect across all three biopolymer levels indicates that the presence of biopolymer has no impact on the shear response at this rate under submerged conditions, and so a similarly consistent reduction is expected in all submerged specimens. Whilst the absolute strengths of submerged specimens may therefore be slightly reduced, the observed trends and behaviour are considered to be representative of real behaviour. The viscoelasticity of EPS is responsible for soil particle adhesion and aggregation (Burmølle et al. 2011; Flemming and Wingender 2010) but with sufficient water in the soil, xanthan gum will remain sufficiently hydrated that molecular interactions are minimised (Wassen et al. 2014) and increased adhesion and shear strength effects are not noticeable. A similar lack of effect of 0.5% moist xanthan gum on sand was observed by Lee et al. (2017).

Drying of pure sand caused no significant difference to the material's shear behaviour as compared to its initial state, but the drying of biopolymer-amended specimens led to significant shear strength increase (Figure 1c) as observed in previous studies (Chang et al. 2016). This has been attributed to increasing molecular interaction and bonding as molecule proximity increases with removal of intermolecular water layers, and causes the biopolymer gel to shrink and bind sand particles together to increase overall soil cohesion and shear strength. Biopolymer glass transition temperatures are strongly affected by the degree of hydration (Grunina et al. 2006) – at low moisture they behave as glassy, brittle materials whilst at higher levels they are plastic. However, it is likely that the distribution of biopolymer gel in the sand is non-uniform at the scale of individual grains, particularly at the 0.1% concentration, and so non-homogeneous aggregations may form which likely lead to the observed variability in shear strength (Chang et al. 2016). This variability decreases slightly with increasing normal stress, suggesting that greater effective stress in the sand skeleton and an increasing contribution of intergranular friction helps to distribute the stress response more evenly, with zones less affected by biopolymer strengthening increasingly contributing to strength by frictional means.

Dried 0.1% biopolymer specimens exhibited a much greater peak friction angle than was observed with any other group of specimens (50.4º compared to 37.1º with dried sand only). Although there is some variability between replicates, this does not account for the increase. Higher angles of friction are often attributed to greater angularity or reduced sphericity of particles (Podczeck and Miah 1996; Shinohara et al. 2000), and one possible cause could be increased irregular aggregation caused by small amounts of biopolymer distributed non-evenly and subsequent interlocking of aggregates. Such an effect was not observed with 0.5% biopolymer, possibly because the biopolymer is more evenly distributed and does not create single aggregates and so the major effect is on cohesion. Drying with 0.5% biopolymer caused a small decrease in friction angle compared to fresh specimens, which may be caused by the larger amount of dried biopolymer acting to keep sand grains apart at these low normal stresses and limit mobilisation of intergranular friction. At both biopolymer contents, drying led to a significant increase in cohesion, although the increase is not linearly related to biopolymer content, with c’ increased by a factor of 5.8 at 0.1% but a far greater factor of 93.3 at 0.5%. This suggests that there is a threshold at which dried biopolymer has a significantly greater effect on cohesion, which is hypothesised to be a similar effect to that noted above, where at 0.5% the amount of biopolymer is sufficient to create a uniformly distributed biopolymer mesh with widespread intergranular biopolymer bridges able to provide additional cohesion and leading to more ‘monolithic’ behaviour. At a level of 0.1% even though the biopolymer is nominally uniformly distributed to begin with the bonds between grains will necessarily be weaker and upon drying the shrinkage that occurs may cause breakage of some bonds. Instead of a monolith, therefore, zones of connected grains would form aggregates.

Lee et al. (2017) observed no strengthening upon drying of 0.5% xanthan gum-treated sand and attributed this to a discontinuous biopolymer matrix within the sand. However, the sand used in their study was coarser than that used here. We therefore suggest there is an increased ability of biopolymer to form resilient intergranular bonds in this well-graded material because of a larger number of contact points and a reduced pore size increasing the chance of formation of biopolymer bridges between grains even at lower biopolymer contents. Chang et al. (2015) observed a similar effect, albeit with soils containing a range of particle types, and attributed the ability of biopolymer to better improve soils with both sand and clay particles to electrostatic interactions between biopolymer and clay particles, and this composite acting as a cementing agent between larger grains. The data presented here indicate that well-graded soils of any type are more likely to be improved by biopolymers due to the greater inter-particle contacts, in a similar manner to the preference for use of well-graded aggregates in cementitious construction materials. The particle size distribution is therefore a key determinant of the impact of biopolymers on shear behaviour.

Effect of moisture path on shear performance

It is demonstrated above that under both original and submerged conditions there is no detectable contribution to strength from biopolymer at any level tested here. Despite this, there are likely to be changes to the structure of the biopolymer present due to dissolution and diffusion or other transport of the polymer molecules in the presence of sufficient moisture. Upon drying there is a considerable change in the structure of the sand/biopolymer composite caused by increased polymer intermolecular interaction and strengthened intergranular bonds leading to either aggregation or monolith formation which causes increases in angle of friction and cohesion respectively. These changes in biopolymer distribution or structure will impact how the composite responds to subsequent moisture changes, and so experiments were performed to explore how a first stage of wetting or drying impacted shear performance following a further change in moisture levels, either reverting to the original state or to a submerged or dried state as appropriate.

Figure 2 presents the impact of two-stage moisture paths on shear behaviour of sand/biopolymer composites at low normal stress with 0.1% biopolymer, whilst those with 0.5% biopolymer are presented in Figure 3. Mohr-Coulomb parameters for these relationships are presented in Table 4. As expected, rewetting of dried specimens (either to submerged [O-D-S moisture path] or original [O-D-O moisture path] states) causes a considerable decrease in peak shear strength compared to the dried state, which may be attributed to absorption of water by the dried biopolymer gel and subsequent swelling. The absorption and permeation of water at the biopolymer-sand interface will induce swelling stresses and decrease biopolymer adhesion. However, with both biopolymer levels the peak shear strength following this rewetting stage was consistently higher than in the original fresh specimens, even when submerged. This was particularly marked with 0.5% biopolymer. This implies that there is a persistent change in the biopolymer structure or distribution in the sand caused by drying. In O-D-S specimens, enhanced strength over original conditions was observed even though after submersion without drying reduction in strength was observed (Figure 1). Also, whilst in O-D-O specimens we cannot be certain that the reintroduced moisture has fully been absorbed by the gel or whether a portion is retained in menisci between grains separate from gel molecules, the similarities between O-D-O and O-D-S specimens (particularly with 0.5% biopolymer) suggest that matric suction arising from any free water is not a major contributor to the observed residual strength.

When previously submerged specimens are slightly dried to return to their original moisture condition (O-S-O moisture path), the peak shear strength and Mohr-Coulomb parameters (Table 4) also revert to values very similar to those observed originally. Further drying (O-S-D moisture path) causes substantial increases in cohesion compared to the original state, as expected and as previously observed with the original drying path (O-D moisture path). However, and with both levels of biopolymer, the strength increase following a submerged stage is considerably lower than that observed without a submerged stage – with 0.1% biopolymer, including the submerged stage reduces cohesion from 18.4 to 10.2 kPa, whilst with 0.5% it reduces cohesion from 298.4 to 78.9 kPa. The peak angle of friction after the O-S-D path (0.5% biopolymer) is considerably lower than with other data (Table 4), although this may be attributed in part to the considerable variability between replicates (shown in Figure 6b).

Based on these data, we suggest that intergranular bonds form by biopolymer bridging between grains upon mixing of the gel with sand in the original, partly unsaturated, conditions. Upon drying these are reinforced by water loss that permits increased intermolecular secondary bonding. However, if specimens are submerged, this disrupts the original intergranular bridges through gradual dissolution and diffusion of the biopolymer molecules and so upon subsequent drying the strengthening effect of the remaining bridging material is smaller. It is apparent, however, that the strength mobilised in previously dried specimens is not entirely dissipated upon subsequent wetting, demonstrating some resilience of this dried structure. Combining this with the persistence of a biopolymer effect that occurs in the O-D-O and O-D-S moisture paths suggests that when a biopolymer is released into a soil, if it dries first then considerably more strength will be mobilised than if it is wetted first.

Using the data above, stress-moisture paths are presented in Figures 4 (0.1% biopolymer) and 5 (0.5% biopolymer), which illustrate the behaviour of each specimen type under different normal stresses and help to elucidate the impacts of both initial drying or wetting on subsequent behaviour that were not clearly perceptible in the previous discussion. It is clear that the response of shear behaviour to wetting and drying is highly consistent across all conditions.

In all cases, drying of specimens prior to returning to the original moisture content (O-D-O moisture path) leads to a strength improvement, whilst the opposite (O-S-O) leads to a strength reduction with low levels of biopolymer or no substantial difference at higher levels. Comparing two stage to single stage moisture paths, and as noted above, immediate drying from the original state (O-D) produces a far higher peak shear strength than if specimens are submerged before drying (O-S-D). In addition, submerging specimens which have previously been dried (O-D-S) always produces specimens which can mobilise considerably more shear resistance than specimens which have been only submerged (O-S). It is clear from the above that the moisture state of a sand/biopolymer composite is not sufficient to describe its behaviour – the moisture path that a specimen takes to reach a particular state also governs its behaviour.

Response of shear behaviour to multiple drying and wetting cycles

Following the analysis of the effect of moisture path on shear behaviour above, the persistence of the observed effects with multiple moisture cycles was explored. Ten drying and wetting cycles were carried out with the results presented in Figures 6 (0.1% biopolymer) and 7 (0.5% biopolymer) for all three normal stresses employed in this study. Initial behaviour upon drying then wetting is as described above for the O-D-S specimens, with considerable increases in peak strength upon drying followed by loss of the majority of this strength upon subsequent wetting. It should be again noted that not all of the strength increase is lost upon submersion – there is a residual strengthening effect. In addition, the potential development of small pore pressures in testing of wetted specimens suggests that the actual wetted strength observed is slightly lower than that in an undrained condition, so these results are conservative. Further cycles exhibited similar behaviour, although the magnitude of any strengthening gradually decreased with each cycle. Both dried and wetted strengths peak after one (0.1%) or two (0.5%) cycles then gradually decrease – typically the strengths over the first two cycles (either dried or wetted) are quite similar. With 0.1% biopolymer, some degree of strengthening both on the drying and wetting stage was observed up to 5 cycles, thereafter wetting caused a decrease in strength below that observed in the original specimen. With 0.5% biopolymer some degree of strengthening was observed for all ten cycles tested, and therefore would be expected to persist for more than ten cycles. These indicate some resilience to the sand/biopolymer composite even at very low levels of biopolymer, but also indicate that there are gradual changes upon moisture cycling that can ultimately be detrimental to the performance of the composite.

The strength of bonds between sand grains has been shown to be enhanced with wetting and drying cycles in natural systems as upon drying, biopolymers are concentrated into bridges between grains which are resilient to disruption by wetting (Albalasmeh and Ghezzehei 2014; Benard et al. 2018). Albalasmeh and Ghezzehei (2014) demonstrated that over two wetting and drying cycles an improvement in bond strength occurs as drying pushes more biopolymer towards the intergranular bond. Such an effect is observed here at the 0.5% concentration, but after this the dried strength decreases with increasing numbers of cycles, as similarly observed by Chang et al. (2017). At 0.1% strengthening is maximised after the first cycle before a decrease in dried strength over subsequent cycles. This suggests that if there is a sufficient supply of additional biopolymer (and an absence of any removal mechanisms) bonds may grow in strength but that there is an additional competing mechanism that causes loss of intergranular bond strength. Following the argument in the previous section, we hypothesize that the initial intergranular bonds are stable or enhanced over the first few cycles where there is sufficient biopolymer material to flow towards and maintain or strengthen the intergranular bridge upon drying. At the same time, the dissolution and diffusion during a wetting cycle allows biopolymer to spread away from the initial bond locations, which is likely to associate with grain surfaces through secondary bonding, effectively spreading out the biopolymer over a larger surface area over multiple cycles and reducing the impact of the biopolymer at contact points between grains. More uniformly distributed biopolymer may still offer some cohesion at contact points, but may also help to reduce friction, i.e. lubricating the grain contacts. This gradual change will increasingly counteract the strengthening effect of intergranular bonds and ultimately produce the decrease in shear strength observed. However, on drying, there are still contact points and so there is still an improvement over the original strength, albeit reduced compared to initial cycles. This hypothesis is illustrated in Figure 8 for a considerably simplified system of uniform particle size and biopolymer distribution. In reality, factors such as the presence of a range of particle sizes and shapes, as well as the amount and distribution of biopolymer, will increase the complexity of the biopolymer behaviour over and above that presented in Figure 8 and so further investigation into the nature of the biopolymer behaviour is required to explicitly confirm the causes of our observations.

Data from Figure 6 and 7 have been analysed to determine the Mohr-Coulomb failure parameters and their variation with increasing numbers of drying and wetting cycles, which is presented in Figure 9. Data for both biopolymer concentrations are presented, after both drying and wetting cycles, apart from peak angle of friction for 0.5% dried biopolymer, which exhibited considerable variability (fluctuating between -7 and +56º). We believe this latter issue to be a function of the more uniformly cemented state of the material and the considerable variability between replicates, where the very large cohesion increase masks any real changes to the frictional behaviour. Both peak angle of friction and cohesion follow the same overall behaviour observed previously, namely by increasing over the first one or two cycles then gradually decreasing. This suggests that the observed response is not simply caused by changes to the cohesion of the specimen, as might be expected, but also a change in the frictional behaviour of the material. Following from earlier discussion, we hypothesise that this arises due to increasing movement of the gel from forming strong intergranular bonds to being more uniformly distributed around the grains. If this contributes a lubrication effect upon wetting (again as hypothesised above), it would decrease the angle of friction with increasing numbers of cycles, as observed in Figure 9.

In real near-surface soil systems, the competing effects of new biopolymer production by living organisms and natural degradation processes will impact on the location and form of the biopolymer matrix and its response to drying and wetting cycles. There is the potential for newly produced biopolymer to cause the initial strengthening seen over the first few cycles to be maintained for longer periods as it builds upon existing material, helping the contribution of biopolymer to geotechnical performance of near surface soils to persist rather than decay. In this work, we have explored the potential scale of the effect of biopolymer amendments under highly controlled conditions. The field-scale response will be highly dependent on environmental factors, including climate and levels and type of vegetation, and so will be transient and complex.

Conclusions

The impact of fresh, moist xanthan gum biopolymer at low concentrations (comparable to those expected in nature) on the response of fine to medium well-graded sand to shear loading is not significant, but subsequent changes to the moisture conditions within the ground mean that it can have a significant, if transient, effect. This has the potential to impact larger scale geotechnical behaviour of particulate media, particularly at shallow depths where smaller confining stresses mean that frictional behaviour is less significant compared to cohesive effects. The strength of a biopolymer-amended sand depends not just on the moisture content but also the 'moisture path' taken by this material. Drying of the composite causes significant strengthening, even at very low concentrations of 0.1% (1 mg/g dry mass), whilst wetting appears to cause little change. However, the effect of subsequent drying or wetting cycles is dependent on previous moisture states, with previously dried specimens retaining some strength on submersion and previously wet specimens not achieving as high a strength when dried. We suggest that moisture cycling causes redistribution of the biopolymer from relatively strong, localised intergranular bridges to a more uniform distribution around sand grains which whilst maintaining a degree of cohesion (especially upon drying) may reduce overall friction (particularly at the low confining stresses employed here), reducing the friction angle with cycling. Such effects have been seen at low biopolymer contents, considered to be representative of levels seen in surface soils, and which therefore demonstrate the potential for impacts upon the geotechnical behaviour of surface soil.

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Table 1. Properties of sand used in all experiments

Specific gravity	2.65
D_{10} (mm)	0.095
D_{30} (mm)	0.167
D_{60} (mm)	0.229
Coefficient of uniformity C_u	2.41
Coefficient of gradation C_g	1.28

Table 2. Moisture paths applied to sand/biopolymer composite samples.

Moisture path	Description
O-D	Samples in the original state (O) are dried to constant weight (D) [3 samples]
O-S	Samples in the original state are fully submerged (S) [3 samples]
O-D-O	Samples in the original state are dried to constant weight then rewetted to the original condition [3 samples]
O-D-S	Samples in the original state are dried to constant weight then fully submerged [3 samples]
O-S-O	Samples in the original state are fully submerged then dried until they reach the original condition [3 samples]
O-S-D	Samples in the original state are fully submerged then dried to constant weight [3 samples]
Dry-wet cycles	Samples in the original state are dried to constant weight then fully submerged; these dry-wet cycles were then repeated up to ten times, with 3 samples tested after 1, 2, 5 and 10 cycles.

Table 3. Mohr-Coulomb failure parameters determined from linear regression of data presented in Figure 1.

Biopolymer content (%)	Moisture path	c' (kPa)	ϕ_p' (º)
0.0	O	3.7	36.7
	O-D	3.2	37.1
	O-S	0.9	34.3
0.1	O	3.7	36.5
	O-D	18.4	50.4
	O-S	1.1	33.4
0.5	O	3.8	35.8
	O-D	298.4	33.2
	O-S	1.1	33.8

Table 4. Mohr-Coulomb failure parameters determined from linear regression of data presented in Figures 2 and 3.

Biopolymer content (%)	Moisture path	c' (kPa)	ϕ_p’ (º)
0.1	O-D-O	5.2	37.3
	O-D-S	6.7	38.2
	O-S-O	2.8	34.6
	O-S-D	10.2	34.5
0.5	O-D-O	23.6	38.3
	O-D-S	17.3	47.2
	O-S-O	3.8	36.2
	O-S-D	78.9	25.6

Figure Captions

Figure 1. Coulomb diagrams for original (O), original-dried (O-D) and original-submerged (O-S) moisture paths for a) 0% b) 0.1% and c) 0.5% xanthan gum. Note that Figure 1c has a split y-axis to better display the original-dried specimen data.

Figure 2. Impact of moisture path on shear performance with sand amended with 0.1% biopolymer.

Figure 3. Impact of moisture path on shear performance with sand amended with 0.5% biopolymer. Data for 'original' specimens on Figure 3b are partly obscured by those for the O-S-O specimens.

Figure 4. Stress-moisture paths for sand/biopolymer (0.1%) composite specimens at varying normal stresses (a – 1 kPa, b – 10 kPa, c – 30 kPa). Solid arrows denote drying paths, dashed arrows denote wetting paths. For codes (e.g. O, O-D-O) see Table 2.

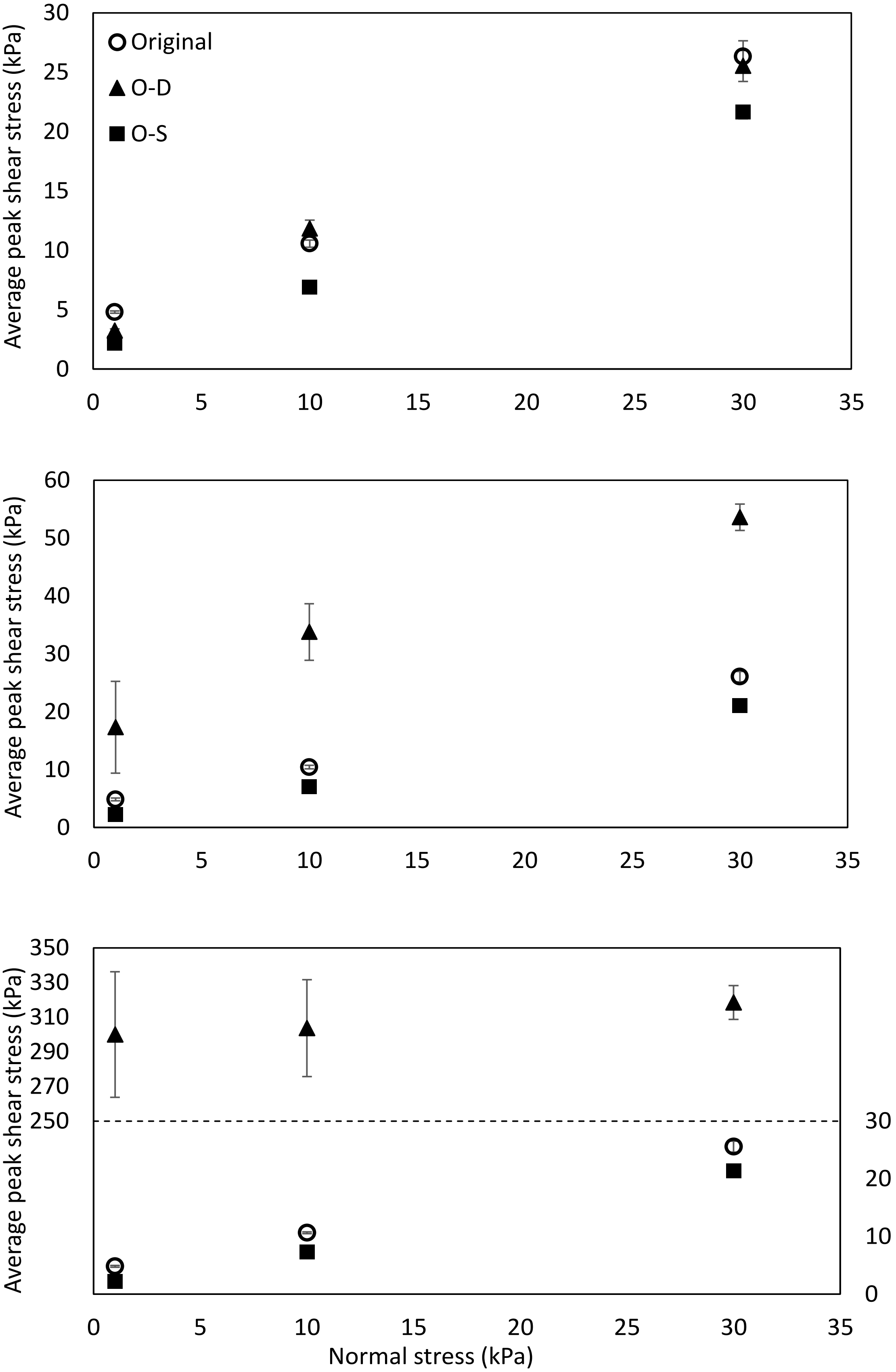
Figure 5. Stress-moisture paths for sand/biopolymer (0.5%) composite specimens at varying normal stresses (a – 1 kPa, b – 10 kPa, c – 30 kPa). Solid arrows denote drying paths, dashed arrows denote wetting paths. For codes (e.g. O, O-D-O) see Table 2.

Figure 6. Peak shear stresses following drying (D) and wetting (W) cycles in sand/biopolymer (0.1%) composite specimens at varying normal stresses (a – 1 kPa, b – 10 kPa, c – 30 kPa).

Figure 7. Peak shear stresses following drying (D) and wetting (W) cycles in sand/biopolymer (0.5%) composite specimens at varying normal stresses (a – 1 kPa, b – 10 kPa, c – 30 kPa). Note that all three sub-figures have a split y-axis to better display the specimen data after drying cycles, with the divide between the two graph portions indicated by a horizontal dashed line.

Figure 8. Simplified conceptual model demonstrating hypothesised motion of biopolymer around surface of idealised, uniform sand grains upon wetting.

Figure 9. Variation in peak friction angle (a) and cohesion (b) with wet and dry cycles. Circles represent 0.1% gel-amended specimens whilst triangles represent 0.5% specimens. Open symbols represent dried specimens whilst closed symbols represent wetted specimens (no peak friction angle data is presented for 0.5% dried specimens as this data is highly variable). The dashed line in (b) separates the plot into two parts represented by the two different axes.

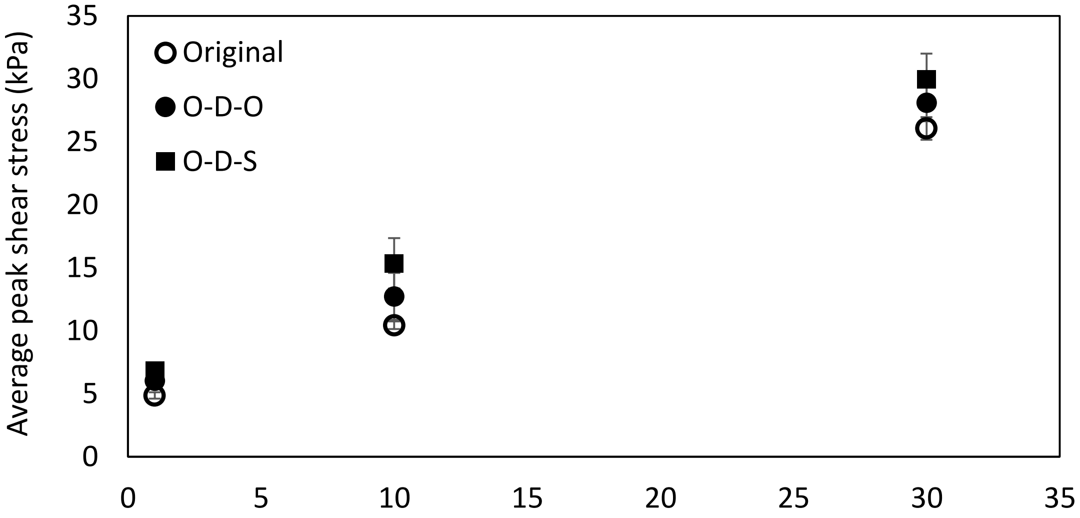


a)

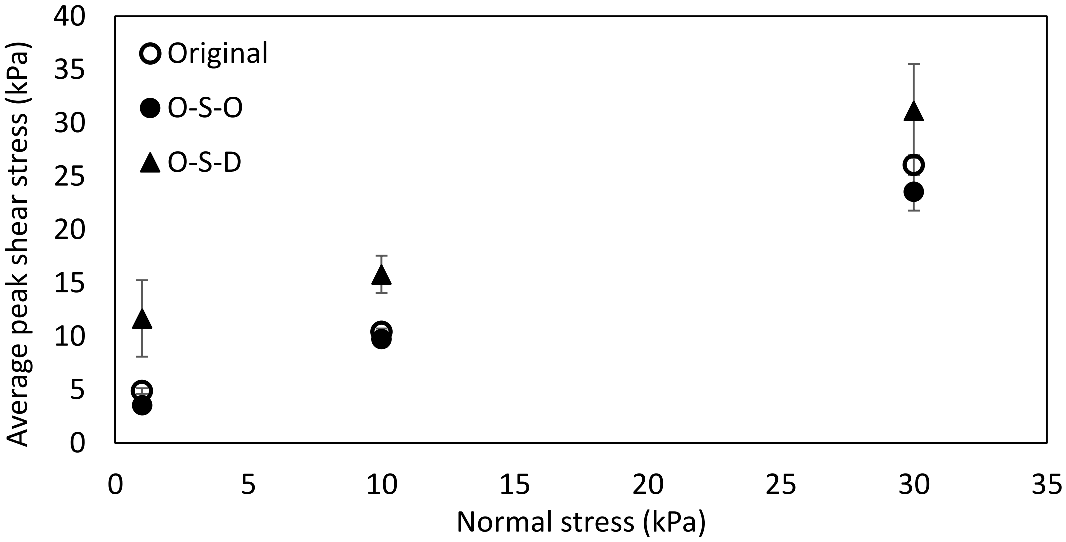
b)

c)

Figure 1. Coulomb diagrams for original (O), original-dried (O-D) and original-submerged (O-S) moisture paths for a) 0% b) 0.1% and c) 0.5% xanthan gum. Note that Figure 1c has a split y-axis to better display the original-dried specimen data.

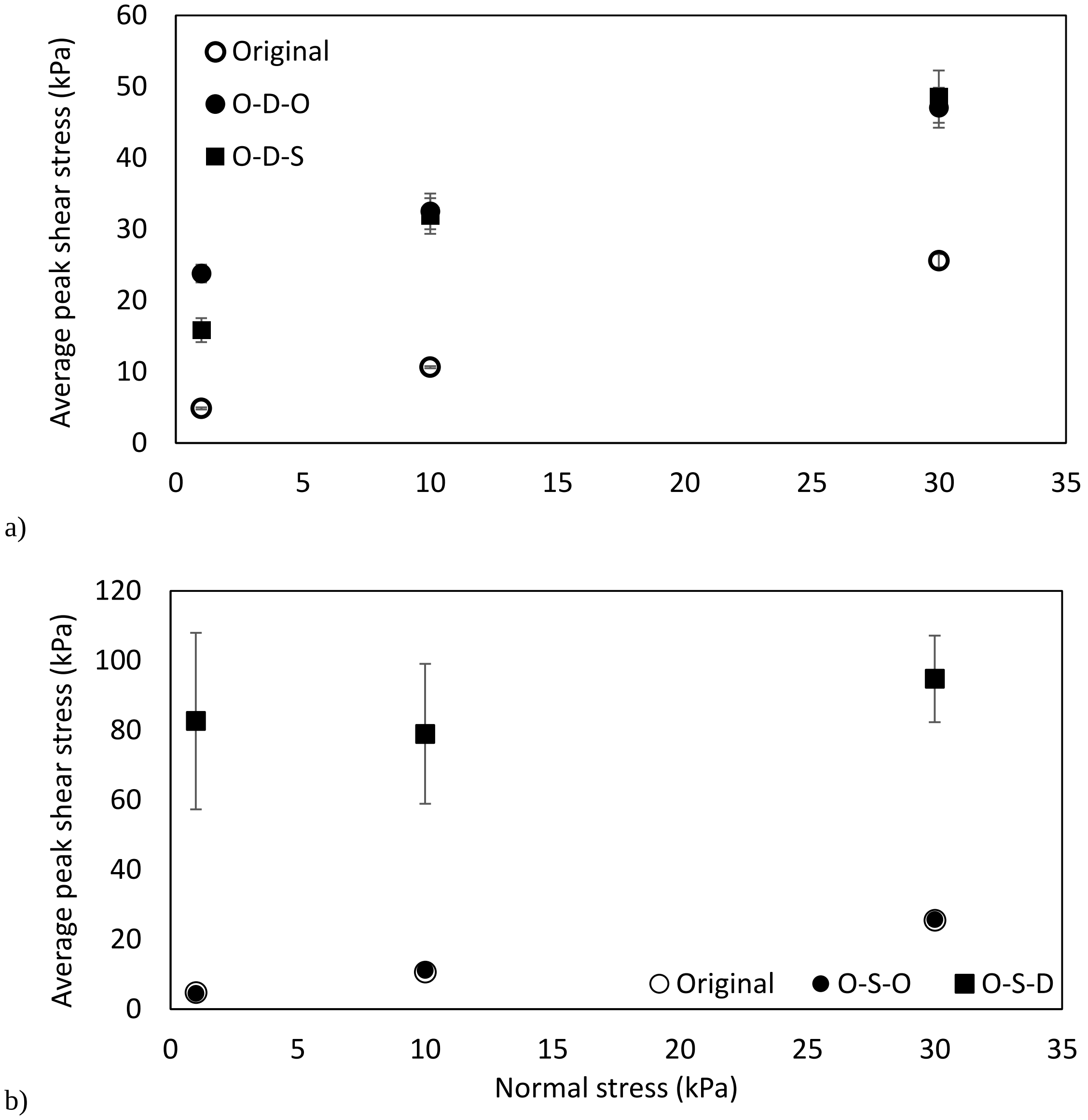


a)



b)

Figure 2. Impact of moisture path on shear performance with sand amended with 0.1% biopolymer.



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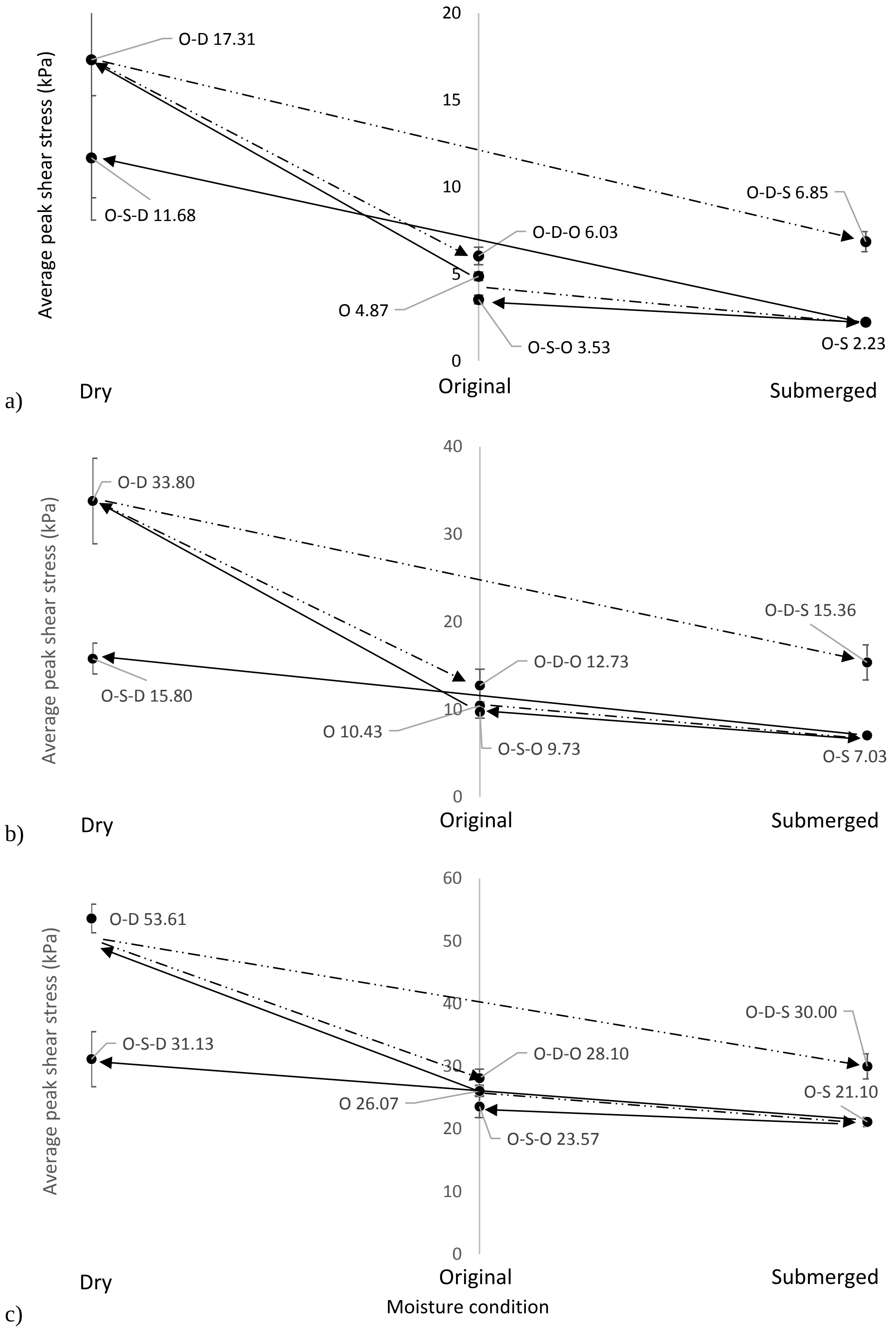
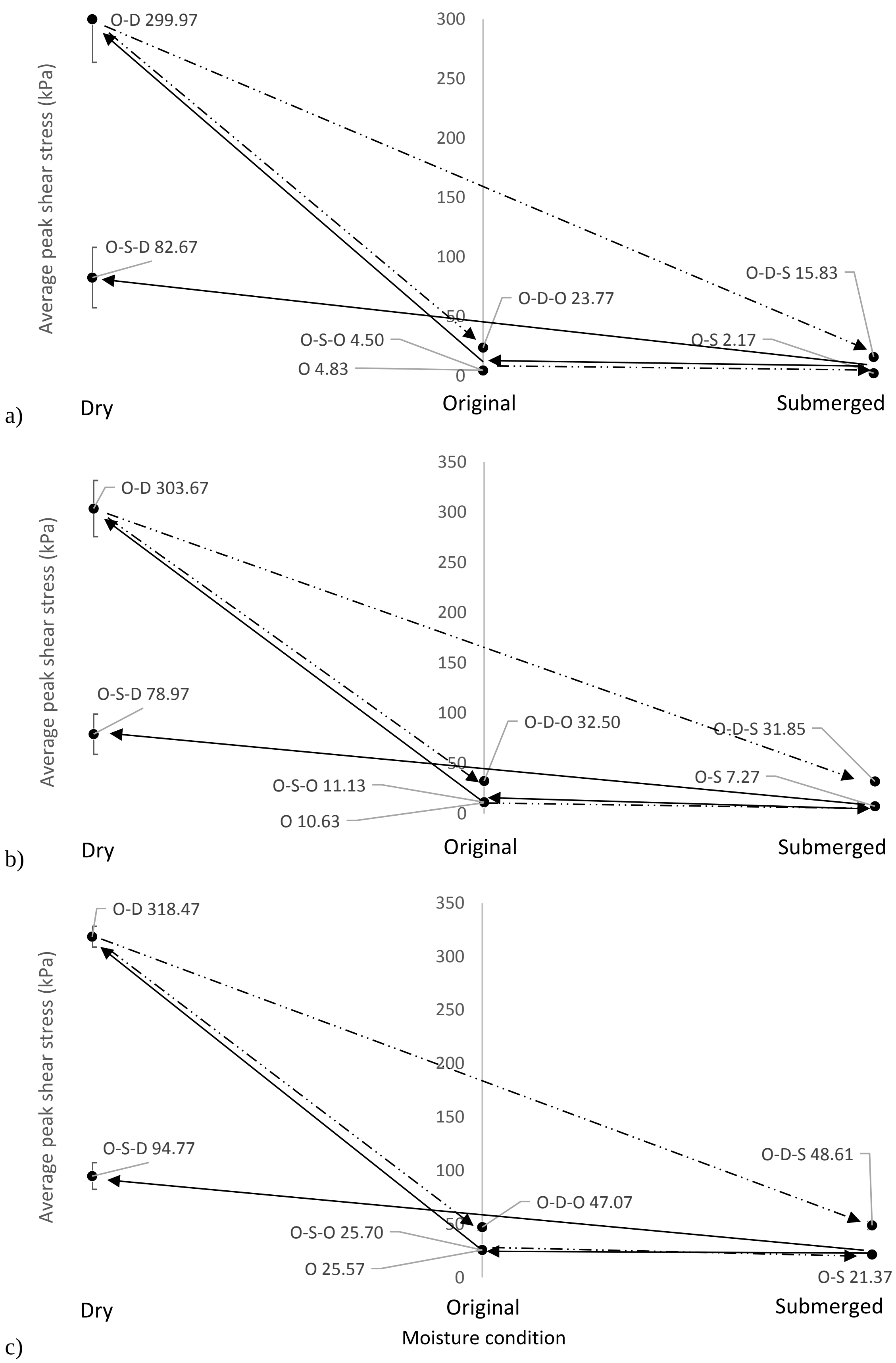


Figure 4. Stress-moisture paths for sand/biopolymer (0.1%) composite specimens at varying normal stresses (a – 1 kPa, b – 10 kPa, c – 30 kPa). Solid arrows denote drying paths, dashed arrows denote wetting paths. For codes (e.g. O, O-D-O) see Table 2.



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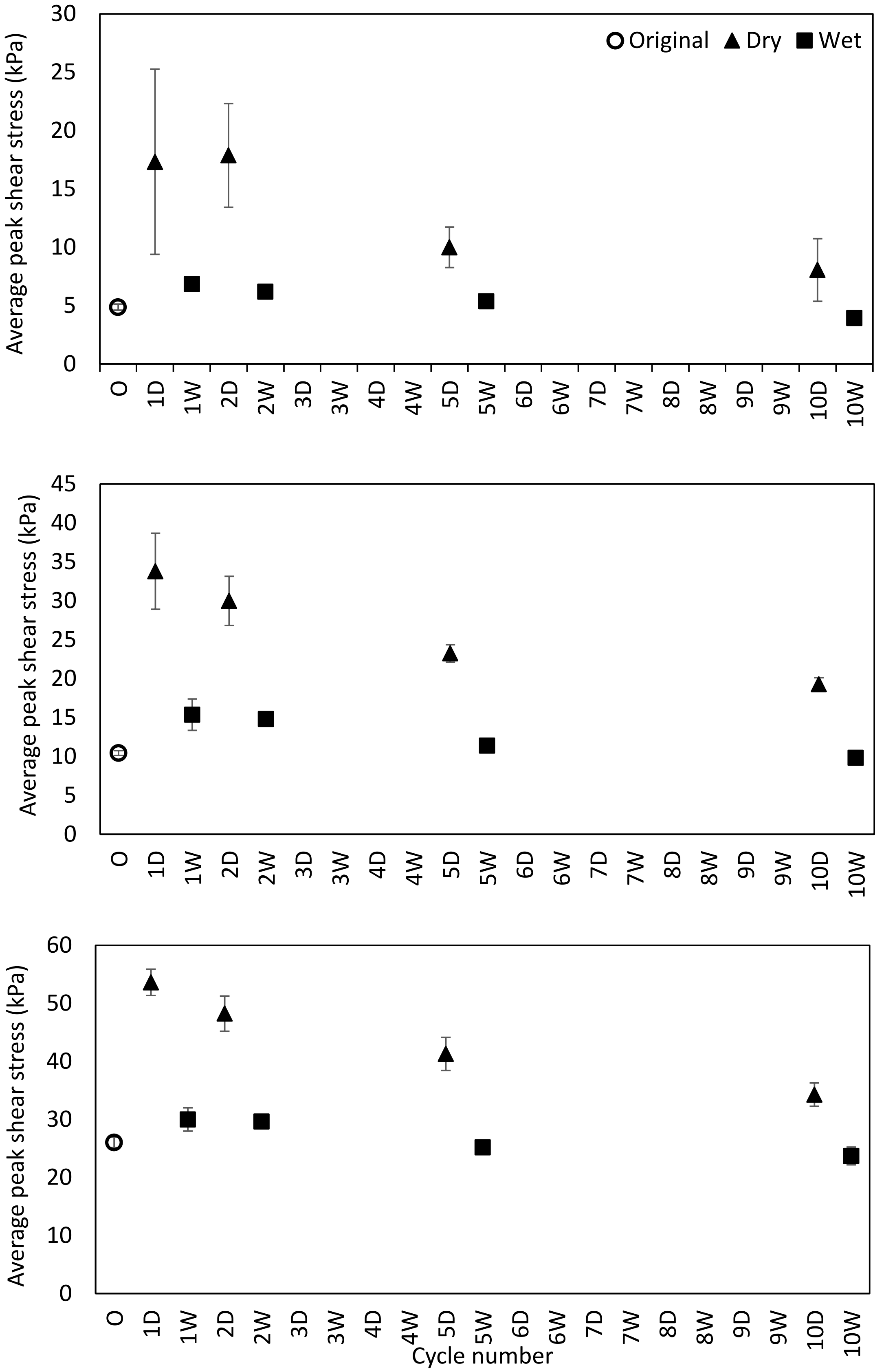

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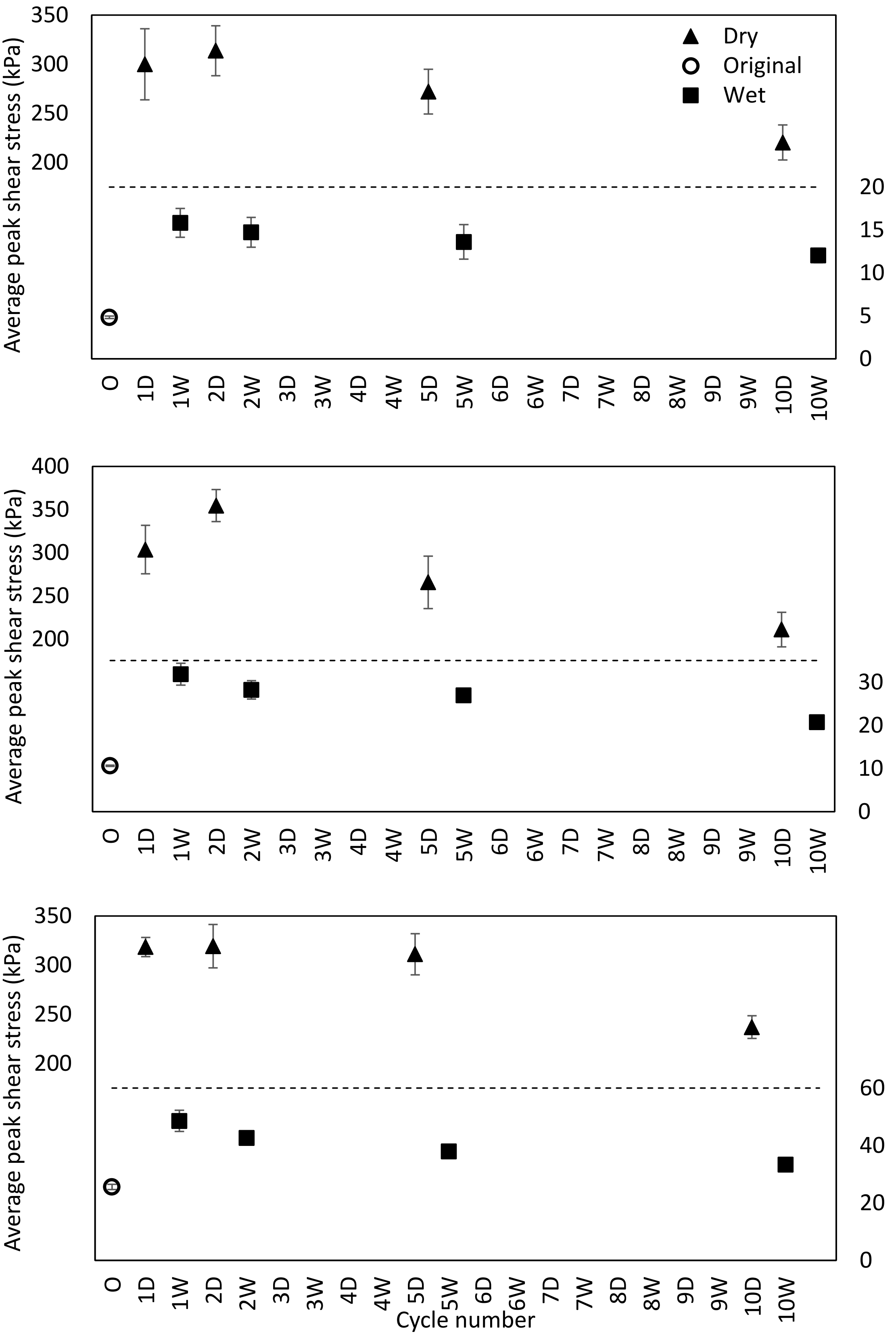
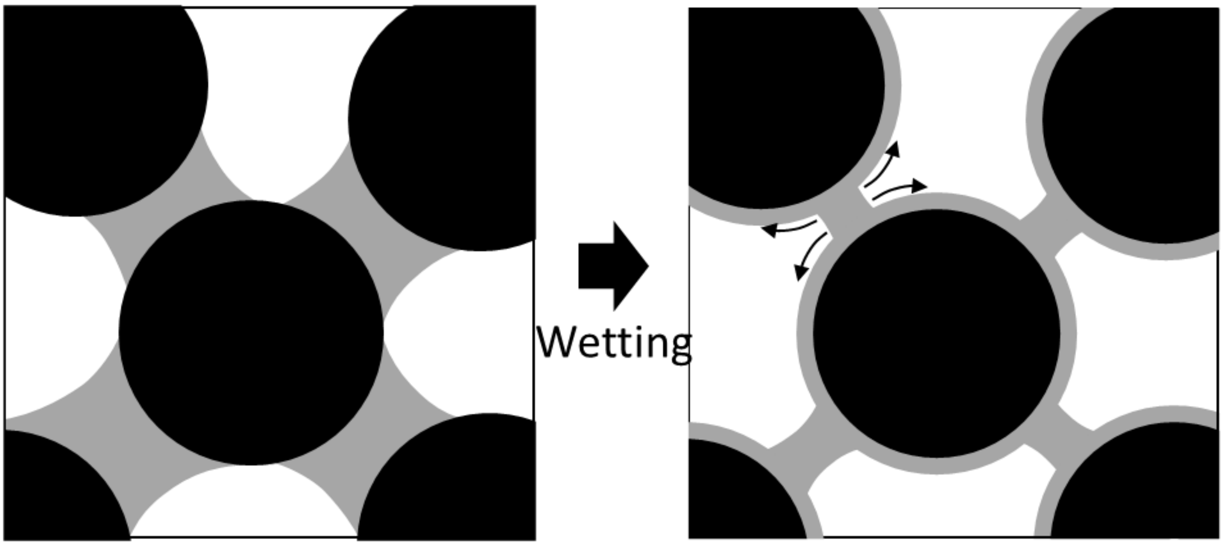


a)

b)

c)

Figure 7. Peak shear stresses following drying (D) and wetting (W) cycles in sand/biopolymer (0.5%) composite specimens at varying normal stresses (a – 1 kPa, b – 10 kPa, c – 30 kPa). Note that all three sub-figures have a split y-axis to better display the specimen data after drying cycles, with the divide between the two graph portions indicated by a horizontal dashed line.



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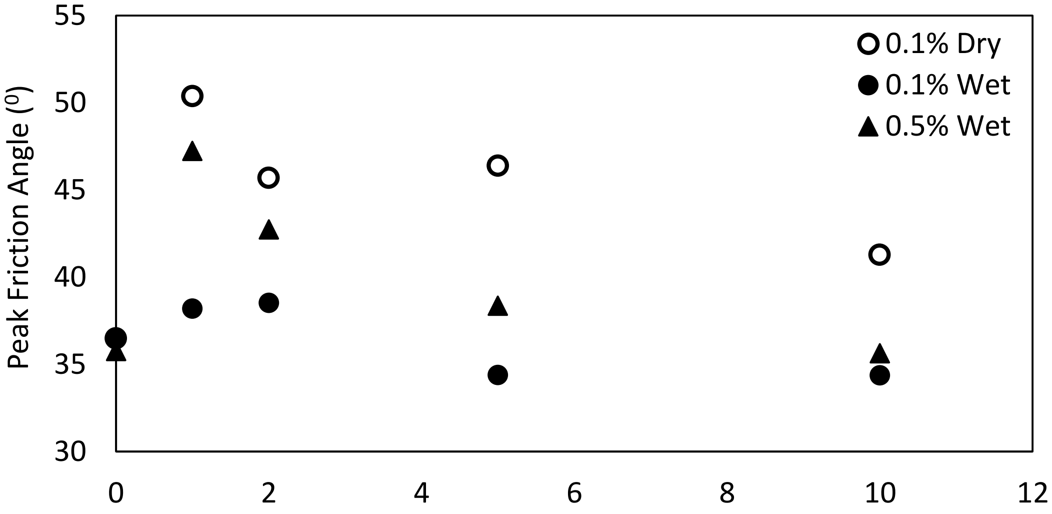
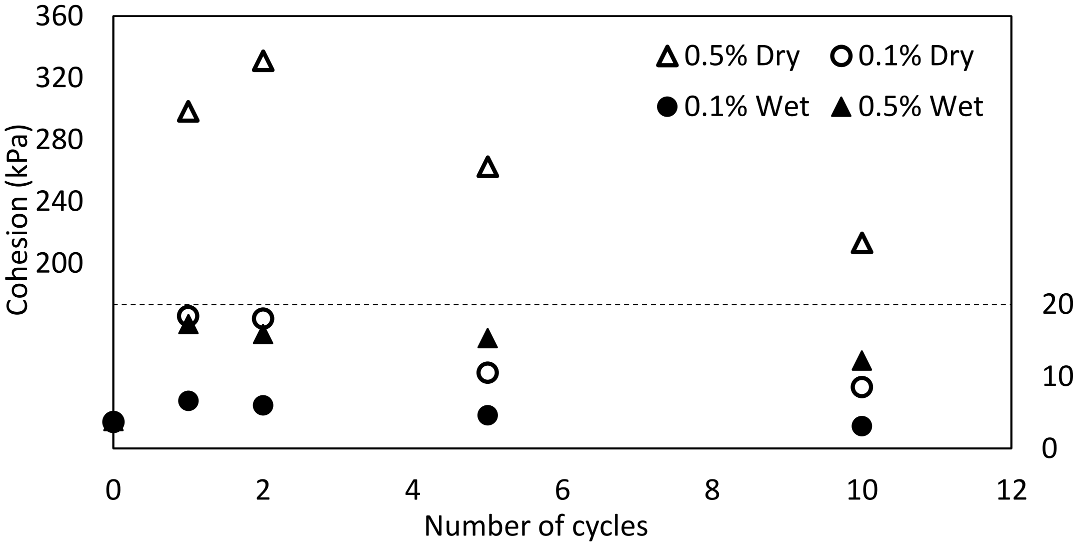


a)



b)

Figure 9. Variation in peak friction angle (a) and cohesion (b) with wet and dry cycles. Circles represent 0.1% gel-amended specimens whilst triangles represent 0.5% specimens. Open symbols represent dried specimens whilst closed symbols represent wetted specimens (no peak friction angle data is presented for 0.5% dried specimens as this data is highly variable). The dashed line in (b) separates the plot into two parts represented by the two different axes.