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

3

4 Chunhui Chen; Li Wu; Michael Harbottle*

5

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

9

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

12

13 Michael Harbottle: * Corresponding author (Email: harbottlem@cardiff.ac.uk; Tel: +44
14 2920875759; Fax: +44 2920874716). Cardiff School of Engineering, Cardiff University, Queen's
15 Buildings, The Parade, Cardiff, CF24 3AA, Wales, UK.

16 **Abstract:**

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

32

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

34

35

36 **Introduction**

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

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

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

62 Biopolymers associated with both microorganisms and plants are readily biodegradable but are
63 produced on a near continuous basis and so whilst there is considerable turnover there is overall a
64 reasonably consistent level of total biopolymer present with values suggested overall of 0.02 to
65 1.4 mg per g dry soil (Chenu 1995), with mucilage contributing an estimated 0.05-50 mg per g
66 dry soil (Zickenrott et al. 2016).

67 Under dry conditions, mucilage can retain water in the soil to help protect roots against
68 desiccation, giving a much higher water content in the rhizosphere compared to the bulk soil
69 (Carminati et al. 2010). Similarly, EPS in biofilm is capable of retaining moisture as protection
70 against desiccation for its inhabitants. The properties of both mucilage and biofilm are hugely
71 influenced by their moisture content and thus the moisture availability in the soil. Both swell and
72 contract substantially as moisture availability increases and decreases and the polymers hydrate
73 and dry (Brax et al. 2017). The mechanical behaviour of biopolymers is greatly affected by this
74 hydration, as with swelling individual molecules interact less with each other whilst with drying
75 interactions increase, secondary bonding increases and the viscosity of the biopolymer gel, and
76 therefore its ability to resist mechanical forces, is greatly enhanced (Wassen et al. 2014).

77 However, moisture changes within the biopolymer mass can be buffered as, for example, changes
78 in biofilm structure as moisture levels change can counteract the effects of the external
79 environment, particularly as the surface adopts a more 'closed' structure upon drying, limiting
80 further moisture loss. The impact of biopolymers on soil geotechnical properties is therefore
81 expected to be affected by changes in moisture availability. Moisture changes can be beneficial,
82 however, causing EPS molecules to become more mobile in moist conditions and allowing a
83 degree of diffusion away from the original source, increasing the interaction of biopolymer
84 molecules with grain surfaces and thus enhancing binding effects (Mager and Thomas 2011).

85 The contribution of typical levels of biopolymer in soil to the geotechnical behaviour of the
86 medium has been explored using a highly controlled artificial sand/biopolymer composite to
87 model natural conditions. This enables the isolation of the effect of biopolymers specifically from
88 other confounding factors, and allows us to determine the potential for natural biopolymers to be

89 managed to enhance or control soil properties. Previously, relatively high levels of biopolymer
90 additives have been considered as a ground improvement agent, with considerable impacts on the
91 mechanical properties of the medium (Cabalar et al. 2018; Chang et al. 2016). However, the
92 behaviour and contribution of lower levels of biopolymer, corresponding to those observed
93 naturally in surface soils, is unknown. The purpose of this study was therefore to use artificial
94 biopolymer to mimic natural biopolymers in the soil, and explore its influence on soil strength
95 under different moisture conditions and moisture paths. A range of moisture conditions including
96 drying, partial wetting, full submersion and drying-wetting cycles were applied to mimic realistic
97 moisture regimes in the soil and to help understand the behaviour of soil/biopolymer composites
98 under natural conditions.

99

100 **Material and methods**

101 *Experimental materials*

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

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

110

111 *Sample preparation*

112 All specimens were prepared within shear box apparatus constructed from Acetal copolymer,
113 designed for applications at low normal stress due to its low density and coefficient of friction,

114 ensuring that the effect of the box on shear stress is minimised. The two halves of these boxes
115 were machined from single blocks of the material with no fixings or adhesives employed in their
116 construction.

117 Dry sand (200 g per shear box) was mixed with xanthan gum gel (40 g per shear box) produced
118 by mixing dry xanthan gum powder with deionised water on a magnetic stirrer for 120 minutes.
119 Two different concentrations of gel (0.5 and 2.5% w/w) were prepared to give dry biopolymer
120 concentrations of 0.1 and 0.5% of the dry sand mass. This corresponds to 1 and 5 mg dry polymer
121 per g dry sand, within the typical ranges quoted for biopolymers in soil given previously. The
122 sand/biopolymer composite was then placed in the shear box and compacted by hand tamping to
123 produce an initial dry density ranging from 1587 kg/m³ to 1603 kg/m³ (void ratio between 0.65
124 and 0.67). The moisture content of 20% allowed for a homogenous final structure, and
125 corresponds to a saturation ratio between 79 and 81% although the moisture is initially bound
126 within the gel rather than being available to form menisci between sand grains.

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

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

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

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

149

150 *Direct shear tests*

151 The effect of biopolymer on the mechanical behaviour of sand was determined using direct shear
152 tests following the British Standard method (British Standard 1377-7: 1990), with adaptations as
153 follows. All tests were performed on a Wykeham Farrance direct shear testing apparatus using
154 shear boxes constructed from Acetal plastic, as discussed above, with low levels of normal stress
155 (1, 10 and 30 kPa) applied using a hanger system apart from at very low stress (1 kPa) where the
156 weight of the top cap was sufficient. The strain rate was 0.8 mm/min – previous studies using
157 direct shear on gum-treated sands (Chang et al. 2016; Lee et al. 2017) employed a rate of 1-1.2
158 mm/min, with substantially higher gum contents. However, the sand used in this study was finer
159 than that used here and so we employed a reduced rate to account for this.

160

161 **Results and analysis**

162 *Biopolymer effect after drying or wetting*

163 The initial impacts of wetting and drying on the shear behaviour of sand/biopolymer composites
164 at low normal stresses are presented in Figure 1 and in general exhibit typical Mohr–Coulomb
165 failure behaviour, with Mohr-Coulomb parameters from this data presented in Table 3. Very good

166 experimental repeatability was observed, apart from dried specimens with both 0.1 and 0.5%
167 biopolymer present where some variability between replicates is noted. The small apparent
168 cohesion values may have arisen in part due to small operational errors, but cannot be attributed
169 to moisture as they were observed even in dried sand without biopolymer. It is apparent that there
170 is little to no effect of fresh biopolymer at either of the levels used on either cohesion or peak
171 angle of friction. Similarly, submersion of the specimens led to no obvious distinction with or
172 without different levels of biopolymer, although a small reduction in both cohesion and peak
173 angle of friction was observed compared to the original state. It is possible that this was caused by
174 small pore pressures developing in submerged specimens only, indicating that the testing rate
175 used may have been slightly faster than desired for these specimens. The consistency of this
176 effect across all three biopolymer levels indicates that the presence of biopolymer has no impact
177 on the shear response at this rate under submerged conditions, and so a similarly consistent
178 reduction is expected in all submerged specimens. Whilst the absolute strengths of submerged
179 specimens may therefore be slightly reduced, the observed trends and behaviour are considered to
180 be representative of real behaviour. The viscoelasticity of EPS is responsible for soil particle
181 adhesion and aggregation (Burmølle et al. 2011; Flemming and Wingender 2010) but with
182 sufficient water in the soil, xanthan gum will remain sufficiently hydrated that molecular
183 interactions are minimised (Wassen et al. 2014) and increased adhesion and shear strength effects
184 are not noticeable. A similar lack of effect of 0.5% moist xanthan gum on sand was observed by
185 Lee et al. (2017).

186 Drying of pure sand caused no significant difference to the material's shear behaviour as
187 compared to its initial state, but the drying of biopolymer-amended specimens led to significant
188 shear strength increase (Figure 1c) as observed in previous studies (Chang et al. 2016). This has
189 been attributed to increasing molecular interaction and bonding as molecule proximity increases
190 with removal of intermolecular water layers, and causes the biopolymer gel to shrink and bind
191 sand particles together to increase overall soil cohesion and shear strength. Biopolymer glass
192 transition temperatures are strongly affected by the degree of hydration (Grunina et al. 2006) – at

193 low moisture they behave as glassy, brittle materials whilst at higher levels they are plastic.
194 However, it is likely that the distribution of biopolymer gel in the sand is non-uniform at the scale
195 of individual grains, particularly at the 0.1% concentration, and so non-homogeneous
196 aggregations may form which likely lead to the observed variability in shear strength (Chang et
197 al. 2016). This variability decreases slightly with increasing normal stress, suggesting that greater
198 effective stress in the sand skeleton and an increasing contribution of intergranular friction helps
199 to distribute the stress response more evenly, with zones less affected by biopolymer
200 strengthening increasingly contributing to strength by frictional means.

201 Dried 0.1% biopolymer specimens exhibited a much greater peak friction angle than was
202 observed with any other group of specimens (50.4° compared to 37.1° with dried sand only).
203 Although there is some variability between replicates, this does not account for the increase.
204 Higher angles of friction are often attributed to greater angularity or reduced sphericity of
205 particles (Podczeczek and Miah 1996; Shinohara et al. 2000), and one possible cause could be
206 increased irregular aggregation caused by small amounts of biopolymer distributed non-evenly
207 and subsequent interlocking of aggregates. Such an effect was not observed with 0.5%
208 biopolymer, possibly because the biopolymer is more evenly distributed and does not create
209 single aggregates and so the major effect is on cohesion. Drying with 0.5% biopolymer caused a
210 small decrease in friction angle compared to fresh specimens, which may be caused by the larger
211 amount of dried biopolymer acting to keep sand grains apart at these low normal stresses and
212 limit mobilisation of intergranular friction. At both biopolymer contents, drying led to a
213 significant increase in cohesion, although the increase is not linearly related to biopolymer
214 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
215 suggests that there is a threshold at which dried biopolymer has a significantly greater effect on
216 cohesion, which is hypothesised to be a similar effect to that noted above, where at 0.5% the
217 amount of biopolymer is sufficient to create a uniformly distributed biopolymer mesh with
218 widespread intergranular biopolymer bridges able to provide additional cohesion and leading to
219 more 'monolithic' behaviour. At a level of 0.1% even though the biopolymer is nominally

220 uniformly distributed to begin with the bonds between grains will necessarily be weaker and
221 upon drying the shrinkage that occurs may cause breakage of some bonds. Instead of a monolith,
222 therefore, zones of connected grains would form aggregates.

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

237

238 *Effect of moisture path on shear performance*

239 It is demonstrated above that under both original and submerged conditions there is no detectable
240 contribution to strength from biopolymer at any level tested here. Despite this, there are likely to
241 be changes to the structure of the biopolymer present due to dissolution and diffusion or other
242 transport of the polymer molecules in the presence of sufficient moisture. Upon drying there is a
243 considerable change in the structure of the sand/biopolymer composite caused by increased
244 polymer intermolecular interaction and strengthened intergranular bonds leading to either
245 aggregation or monolith formation which causes increases in angle of friction and cohesion

246 respectively. These changes in biopolymer distribution or structure will impact how the
247 composite responds to subsequent moisture changes, and so experiments were performed to
248 explore how a first stage of wetting or drying impacted shear performance following a further
249 change in moisture levels, either reverting to the original state or to a submerged or dried state as
250 appropriate.

251 Figure 2 presents the impact of two-stage moisture paths on shear behaviour of sand/biopolymer
252 composites at low normal stress with 0.1% biopolymer, whilst those with 0.5% biopolymer are
253 presented in Figure 3. Mohr-Coulomb parameters for these relationships are presented in Table 4.

254 As expected, rewetting of dried specimens (either to submerged [O-D-S moisture path] or
255 original [O-D-O moisture path] states) causes a considerable decrease in peak shear strength
256 compared to the dried state, which may be attributed to absorption of water by the dried
257 biopolymer gel and subsequent swelling. The absorption and permeation of water at the
258 biopolymer-sand interface will induce swelling stresses and decrease biopolymer adhesion.
259 However, with both biopolymer levels the peak shear strength following this rewetting stage was
260 consistently higher than in the original fresh specimens, even when submerged. This was
261 particularly marked with 0.5% biopolymer. This implies that there is a persistent change in the
262 biopolymer structure or distribution in the sand caused by drying. In O-D-S specimens, enhanced
263 strength over original conditions was observed even though after submersion without drying
264 reduction in strength was observed (Figure 1). Also, whilst in O-D-O specimens we cannot be
265 certain that the reintroduced moisture has fully been absorbed by the gel or whether a portion is
266 retained in menisci between grains separate from gel molecules, the similarities between O-D-O
267 and O-D-S specimens (particularly with 0.5% biopolymer) suggest that matric suction arising
268 from any free water is not a major contributor to the observed residual strength.

269 When previously submerged specimens are slightly dried to return to their original moisture
270 condition (O-S-O moisture path), the peak shear strength and Mohr-Coulomb parameters (Table
271 4) also revert to values very similar to those observed originally. Further drying (O-S-D moisture
272 path) causes substantial increases in cohesion compared to the original state, as expected and as

273 previously observed with the original drying path (O-D moisture path). However, and with both
274 levels of biopolymer, the strength increase following a submerged stage is considerably lower
275 than that observed without a submerged stage – with 0.1% biopolymer, including the submerged
276 stage reduces cohesion from 18.4 to 10.2 kPa, whilst with 0.5% it reduces cohesion from 298.4 to
277 78.9 kPa. The peak angle of friction after the O-S-D path (0.5% biopolymer) is considerably
278 lower than with other data (Table 4), although this may be attributed in part to the considerable
279 variability between replicates (shown in Figure 6b).

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

291 Using the data above, stress-moisture paths are presented in Figures 4 (0.1% biopolymer) and 5
292 (0.5% biopolymer), which illustrate the behaviour of each specimen type under different normal
293 stresses and help to elucidate the impacts of both initial drying or wetting on subsequent
294 behaviour that were not clearly perceptible in the previous discussion. It is clear that the response
295 of shear behaviour to wetting and drying is highly consistent across all conditions.

296 In all cases, drying of specimens prior to returning to the original moisture content (O-D-O
297 moisture path) leads to a strength improvement, whilst the opposite (O-S-O) leads to a strength
298 reduction with low levels of biopolymer or no substantial difference at higher levels. Comparing
299 two stage to single stage moisture paths, and as noted above, immediate drying from the original

300 state (O-D) produces a far higher peak shear strength than if specimens are submerged before
301 drying (O-S-D). In addition, submerging specimens which have previously been dried (O-D-S)
302 always produces specimens which can mobilise considerably more shear resistance than
303 specimens which have been only submerged (O-S). It is clear from the above that the moisture
304 state of a sand/biopolymer composite is not sufficient to describe its behaviour – the moisture
305 path that a specimen takes to reach a particular state also governs its behaviour.

306

307 *Response of shear behaviour to multiple drying and wetting cycles*

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

326 of biopolymer, but also indicate that there are gradual changes upon moisture cycling that can
327 ultimately be detrimental to the performance of the composite.

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

353 sizes and shapes, as well as the amount and distribution of biopolymer, will increase the
354 complexity of the biopolymer behaviour over and above that presented in Figure 8 and so further
355 investigation into the nature of the biopolymer behaviour is required to explicitly confirm the
356 causes of our observations.

357 Data from Figure 6 and 7 have been analysed to determine the Mohr-Coulomb failure parameters
358 and their variation with increasing numbers of drying and wetting cycles, which is presented in
359 Figure 9. Data for both biopolymer concentrations are presented, after both drying and wetting
360 cycles, apart from peak angle of friction for 0.5% dried biopolymer, which exhibited considerable
361 variability (fluctuating between -7 and $+56^\circ$). We believe this latter issue to be a function of the
362 more uniformly cemented state of the material and the considerable variability between
363 replicates, where the very large cohesion increase masks any real changes to the frictional
364 behaviour. Both peak angle of friction and cohesion follow the same overall behaviour observed
365 previously, namely by increasing over the first one or two cycles then gradually decreasing. This
366 suggests that the observed response is not simply caused by changes to the cohesion of the
367 specimen, as might be expected, but also a change in the frictional behaviour of the material.
368 Following from earlier discussion, we hypothesise that this arises due to increasing movement of
369 the gel from forming strong intergranular bonds to being more uniformly distributed around the
370 grains. If this contributes a lubrication effect upon wetting (again as hypothesised above), it
371 would decrease the angle of friction with increasing numbers of cycles, as observed in Figure 9.
372 In real near-surface soil systems, the competing effects of new biopolymer production by living
373 organisms and natural degradation processes will impact on the location and form of the
374 biopolymer matrix and its response to drying and wetting cycles. There is the potential for newly
375 produced biopolymer to cause the initial strengthening seen over the first few cycles to be
376 maintained for longer periods as it builds upon existing material, helping the contribution of
377 biopolymer to geotechnical performance of near surface soils to persist rather than decay. In this
378 work, we have explored the potential scale of the effect of biopolymer amendments under highly

379 controlled conditions. The field-scale response will be highly dependent on environmental
380 factors, including climate and levels and type of vegetation, and so will be transient and complex.

381

382 **Conclusions**

383 The impact of fresh, moist xanthan gum biopolymer at low concentrations (comparable to those
384 expected in nature) on the response of fine to medium well-graded sand to shear loading is not
385 significant, but subsequent changes to the moisture conditions within the ground mean that it can
386 have a significant, if transient, effect. This has the potential to impact larger scale geotechnical
387 behaviour of particulate media, particularly at shallow depths where smaller confining stresses
388 mean that frictional behaviour is less significant compared to cohesive effects. The strength of a
389 biopolymer-amended sand depends not just on the moisture content but also the ‘moisture path’
390 taken by this material. Drying of the composite causes significant strengthening, even at very low
391 concentrations of 0.1% (1 mg/g dry mass), whilst wetting appears to cause little change.

392 However, the effect of subsequent drying or wetting cycles is dependent on previous moisture
393 states, with previously dried specimens retaining some strength on submersion and previously
394 wet specimens not achieving as high a strength when dried. We suggest that moisture cycling
395 causes redistribution of the biopolymer from relatively strong, localised intergranular bridges to a
396 more uniform distribution around sand grains which whilst maintaining a degree of cohesion
397 (especially upon drying) may reduce overall friction (particularly at the low confining stresses
398 employed here), reducing the friction angle with cycling. Such effects have been seen at low
399 biopolymer contents, considered to be representative of levels seen in surface soils, and which
400 therefore demonstrate the potential for impacts upon the geotechnical behaviour of surface soil.

401

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405

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494 the effect of mucilage on soil water repellency. *Journal of Plant Nutrition and Soil*
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496

497 *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

498

499

500 *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.

501

502

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

Biopolymer content (%)	Moisture path	c' (kPa)	ϕ_p' (°)
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

504

505

506 *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' (°)
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

507

508

509 **Figure Captions**

510

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

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

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

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

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

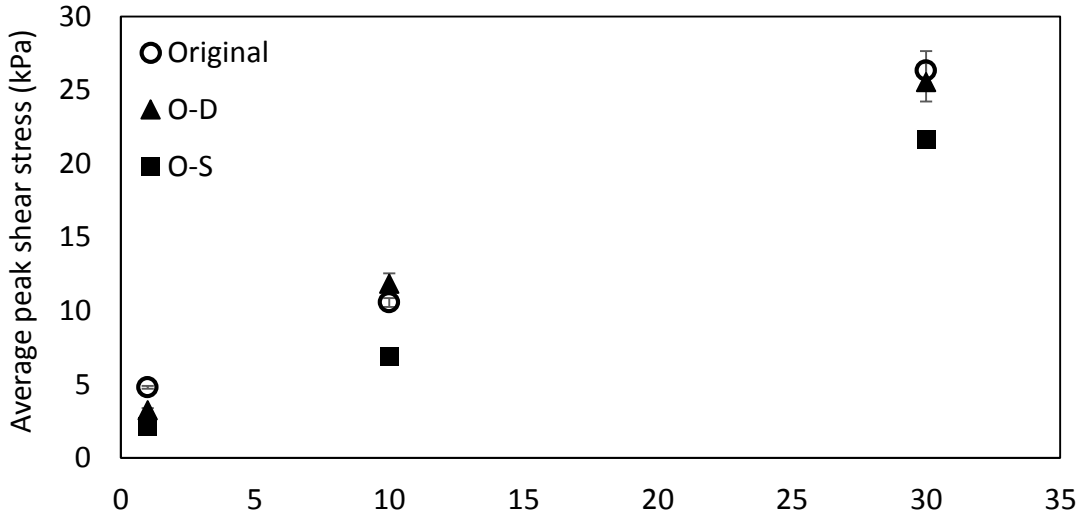
525 Figure 6. Peak shear stresses following drying (D) and wetting (W) cycles in sand/biopolymer
526 (0.1%) composite specimens at varying normal stresses (a – 1 kPa, b – 10 kPa, c – 30 kPa).

527 Figure 7. Peak shear stresses following drying (D) and wetting (W) cycles in sand/biopolymer
528 (0.5%) composite specimens at varying normal stresses (a – 1 kPa, b – 10 kPa, c – 30 kPa). Note
529 that all three sub-figures have a split y-axis to better display the specimen data after drying
530 cycles, with the divide between the two graph portions indicated by a horizontal dashed line.

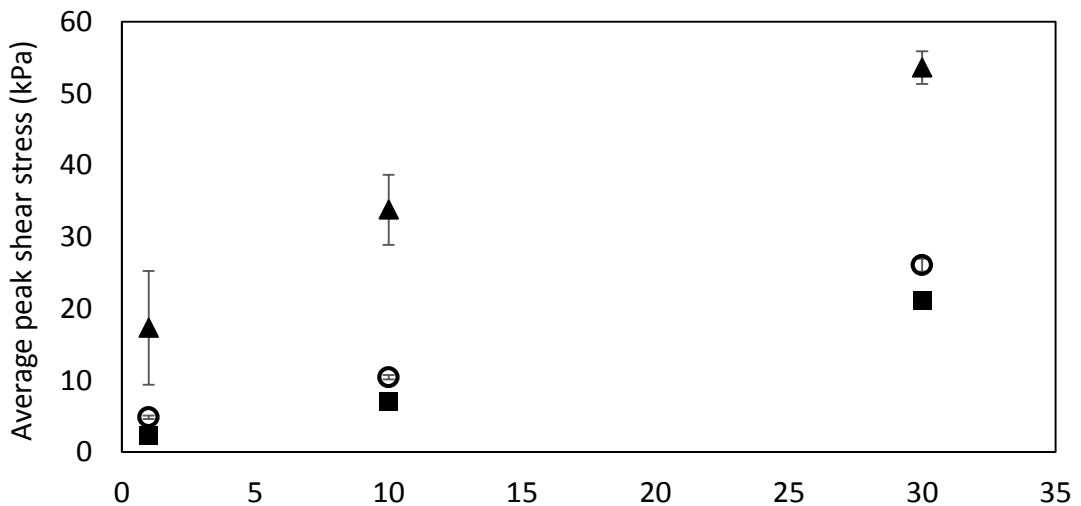
531 Figure 8. Simplified conceptual model demonstrating hypothesised motion of biopolymer around
532 surface of idealised, uniform sand grains upon wetting.

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

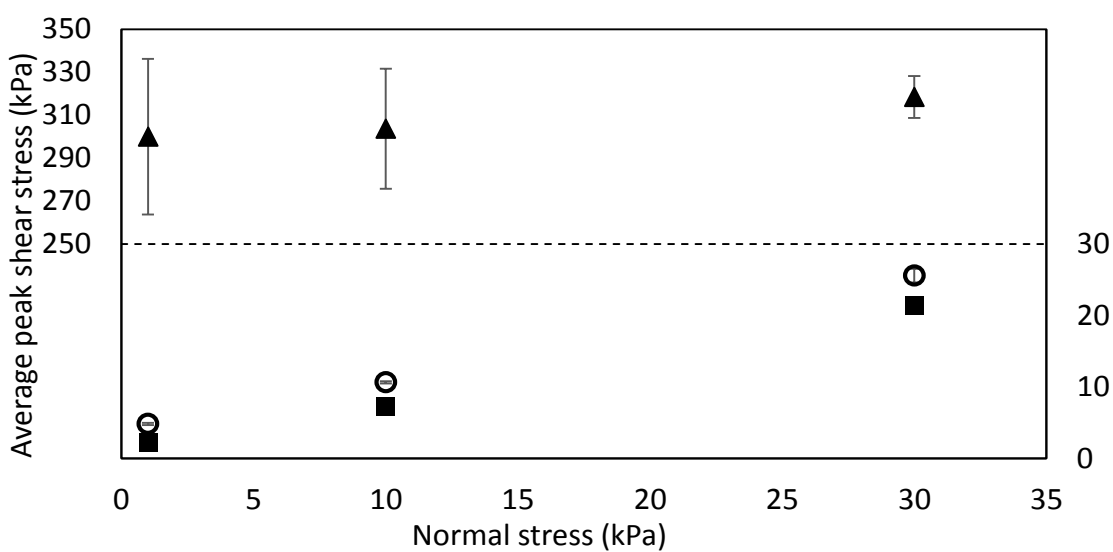
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539 a)

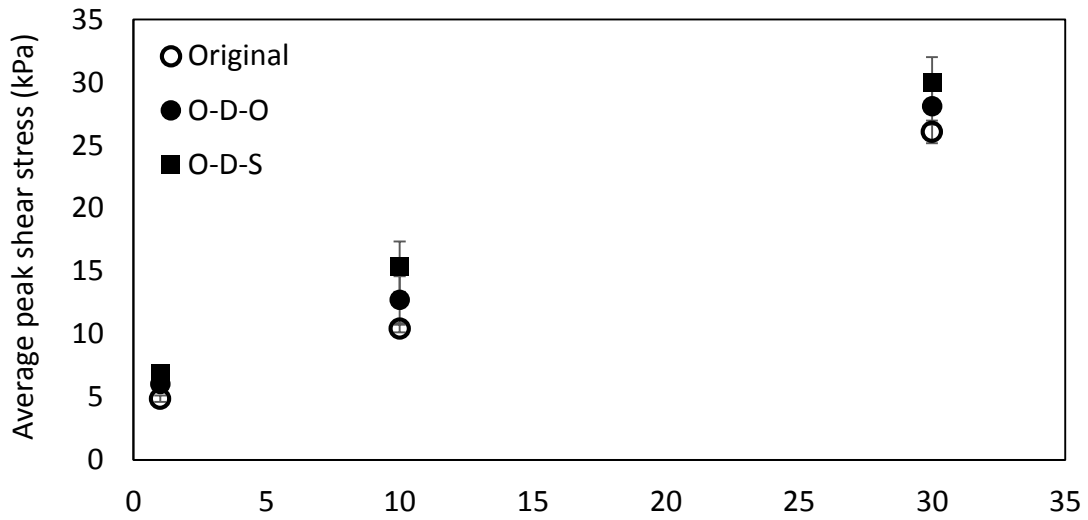


540 b)

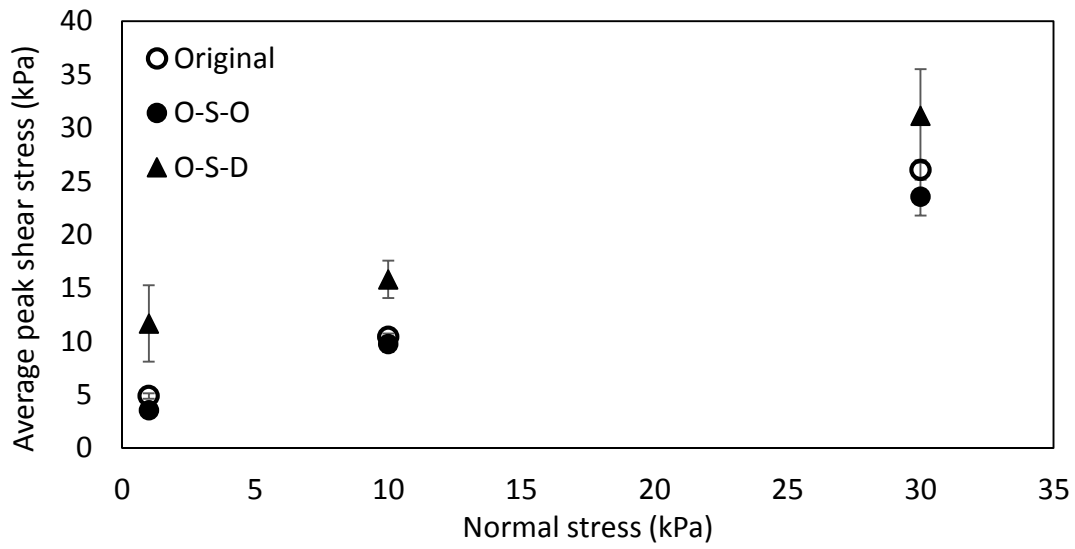


541 c)

542 Figure 1. Coulomb diagrams for original (O), original-dried (O-D) and original-submerged (O-S) moisture paths for a) 0%
 543 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
 544 data.



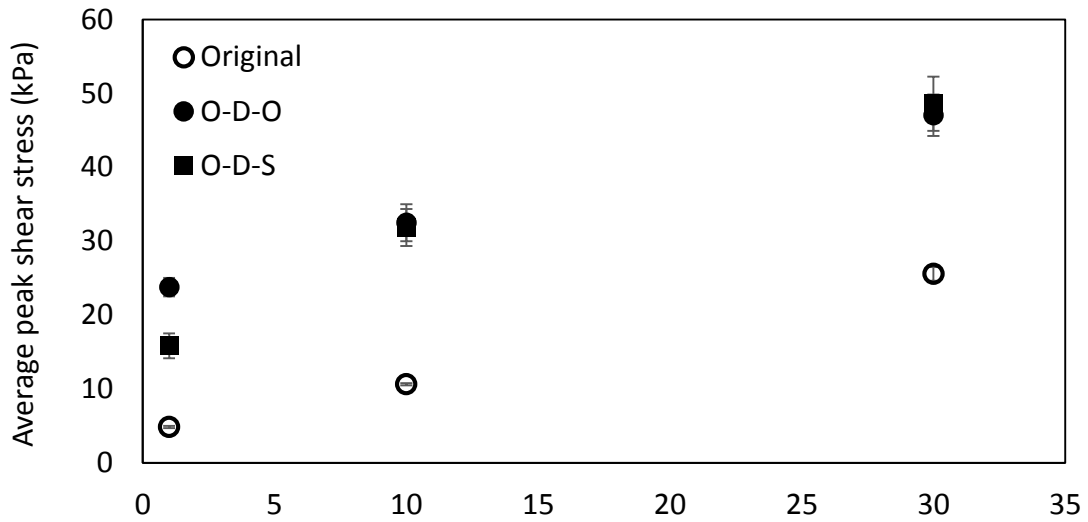
545 a)



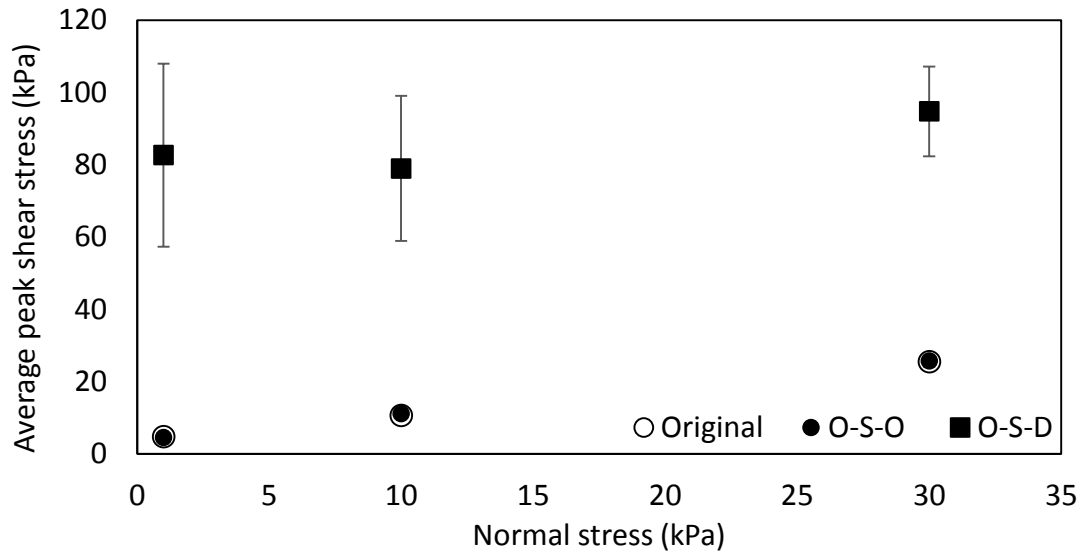
546 b)

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

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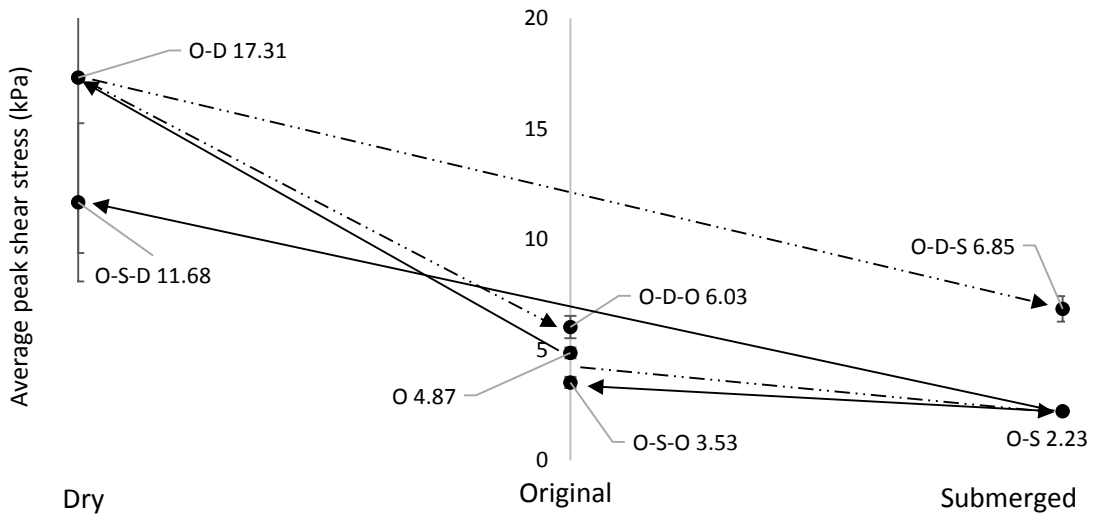
549 a)



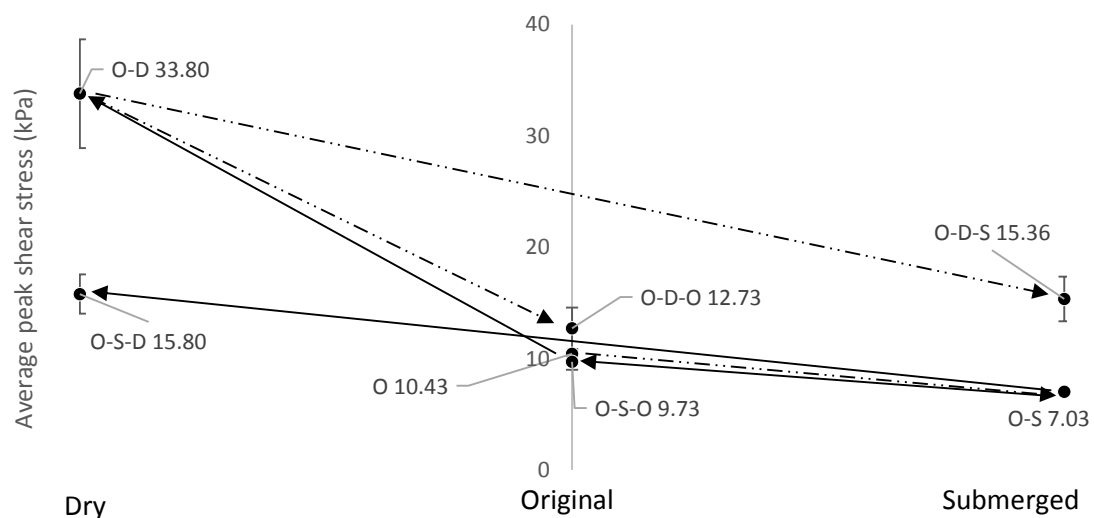
550 b)

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

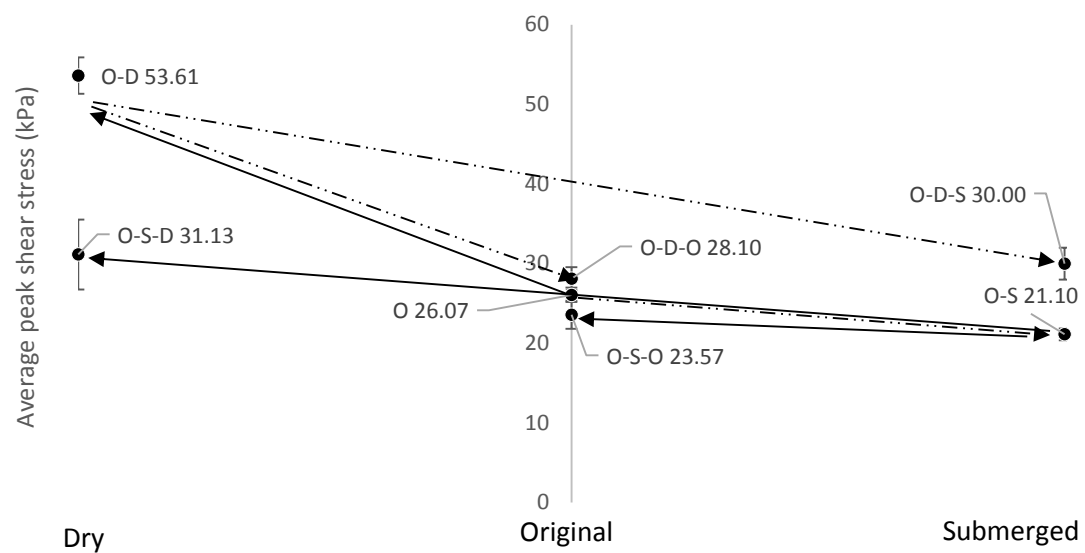
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554 a)

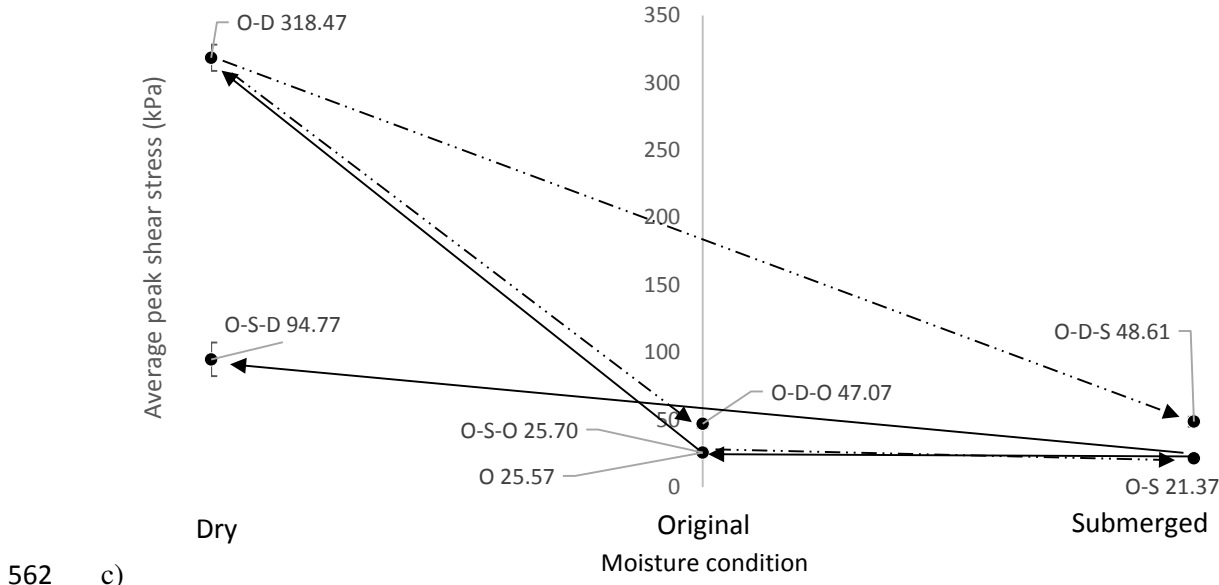
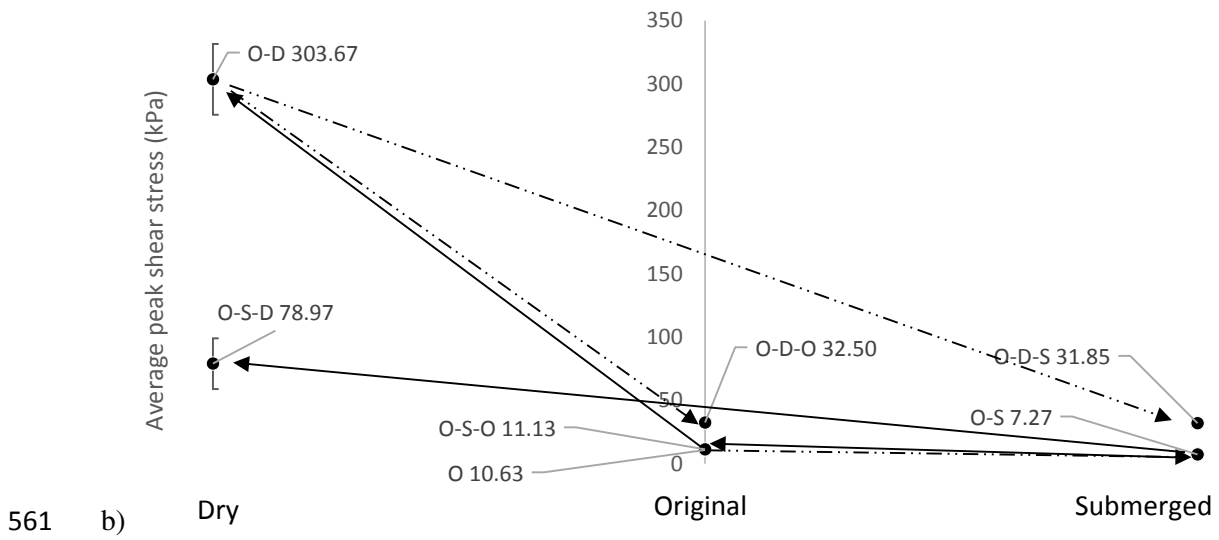
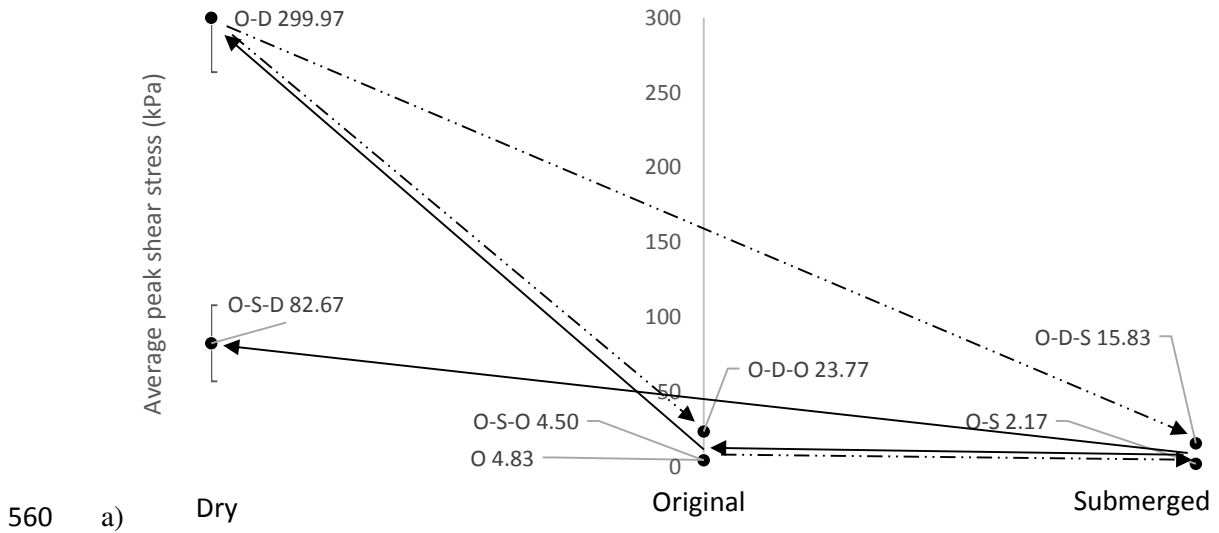


555 b)

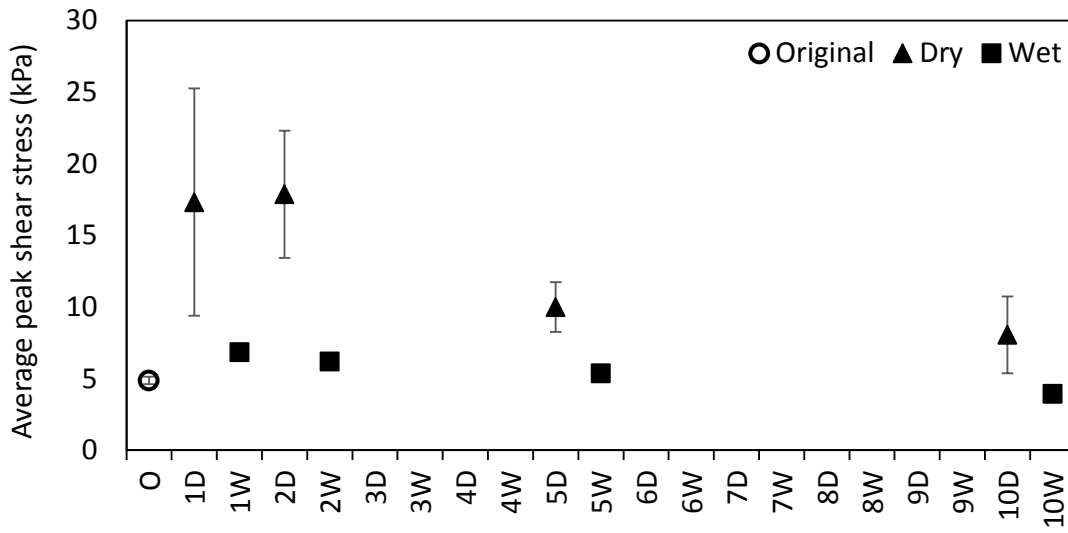


556 c)

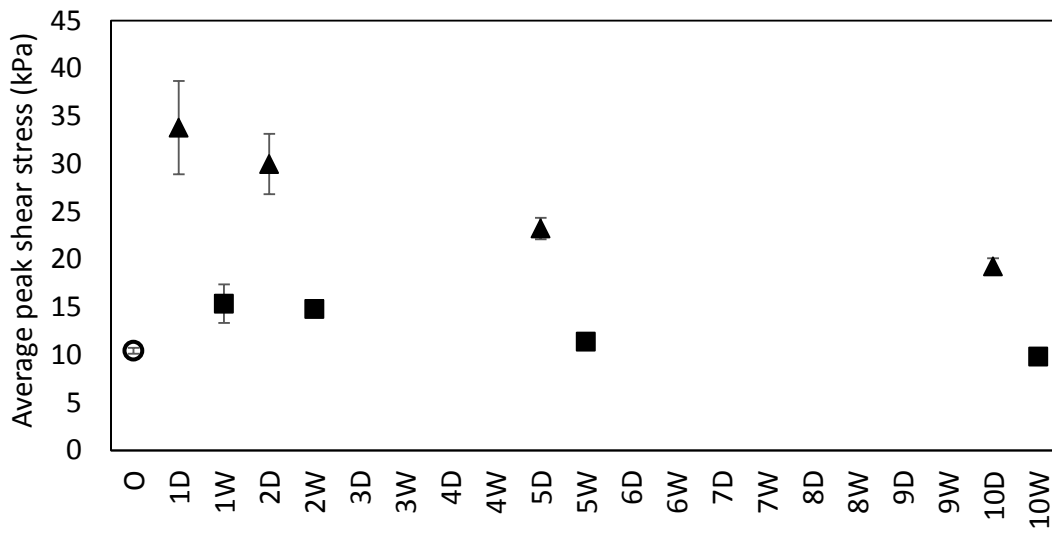
557 Figure 4. Stress-moisture paths for sand/biopolymer (0.1%) composite specimens at varying normal stresses (a – 1 kPa,
 558 b – 10 kPa, c – 30 kPa). Solid arrows denote drying paths, dashed arrows denote wetting paths. For codes (e.g. O, O-D-
 559 O) see Table 2.



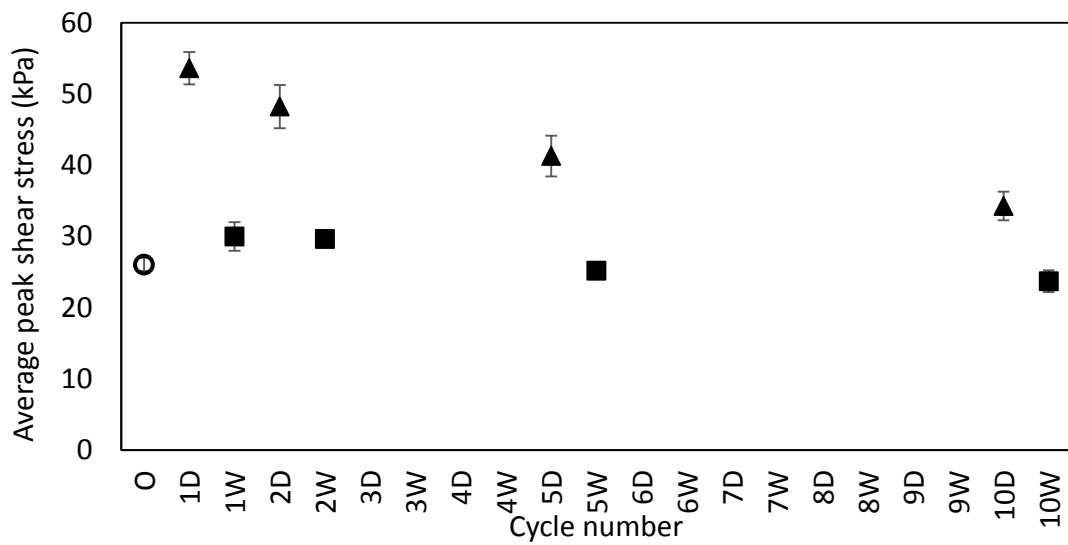
563 Figure 5. Stress-moisture paths for sand/biopolymer (0.5%) composite specimens at varying normal stresses (a – 1 kPa,
 564 b – 10 kPa, c – 30 kPa). Solid arrows denote drying paths, dashed arrows denote wetting paths. For codes (e.g. O, O-D-
 565 O) see Table 2.



566 a)



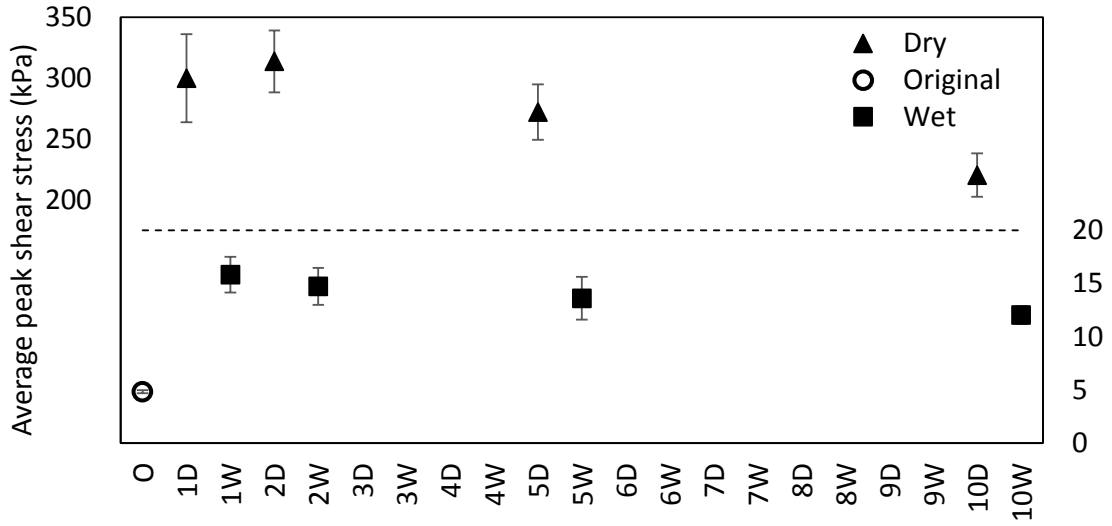
567 b)



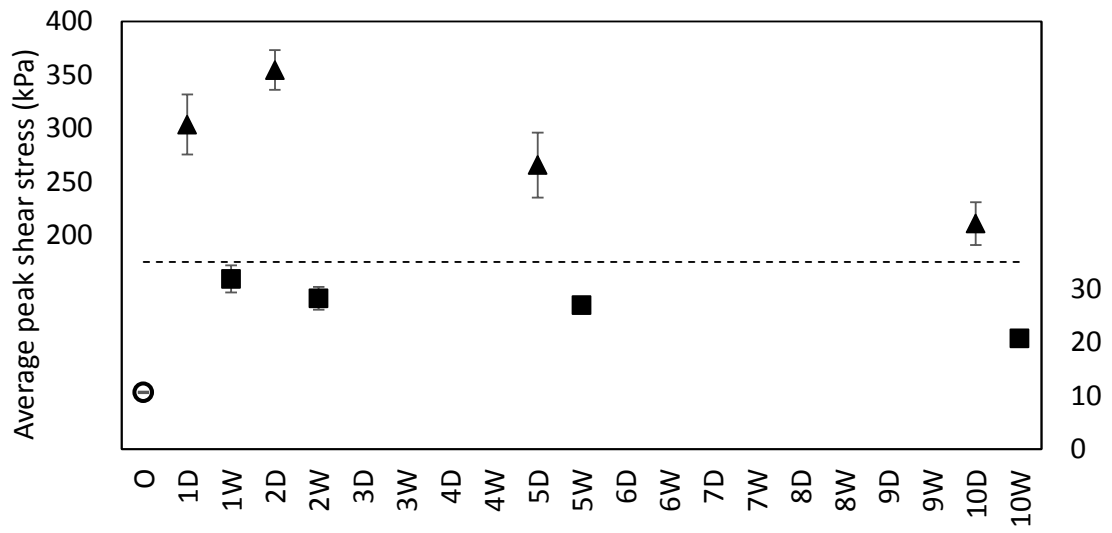
568 c)

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

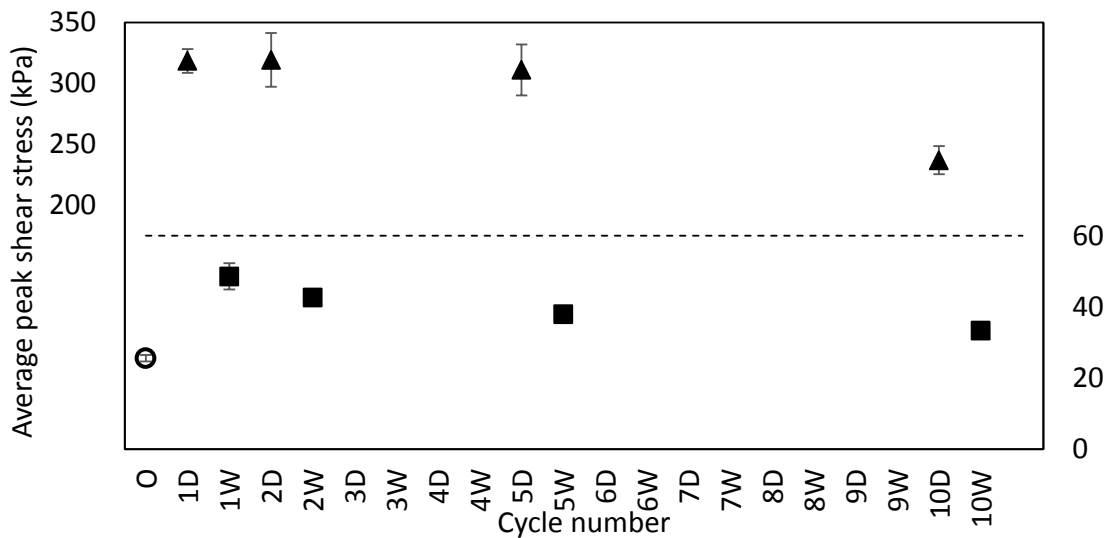
571



572 a)

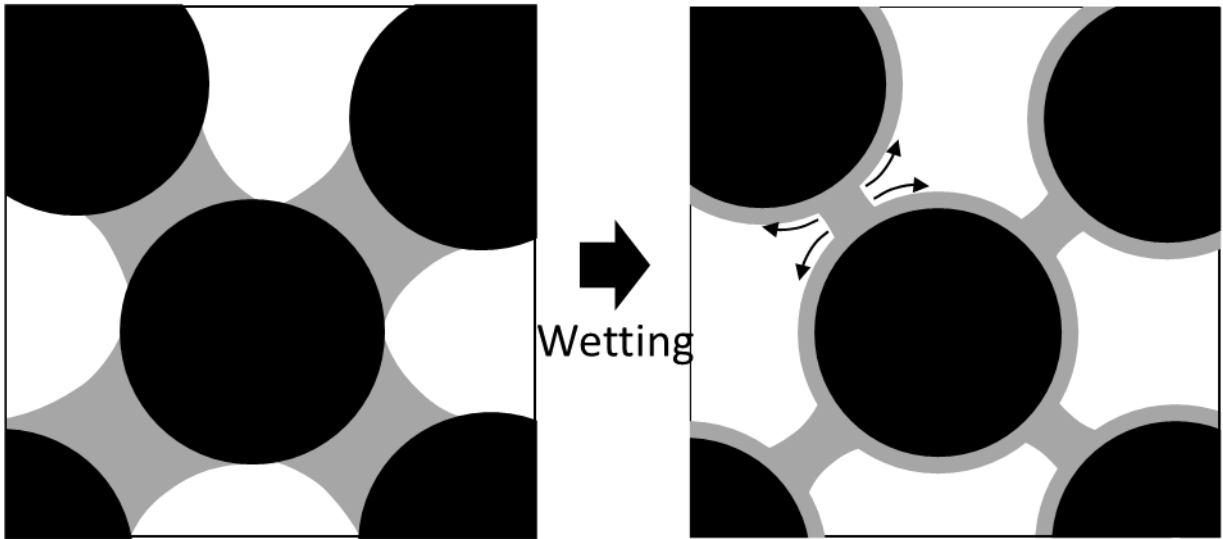


573 b)



574 c)

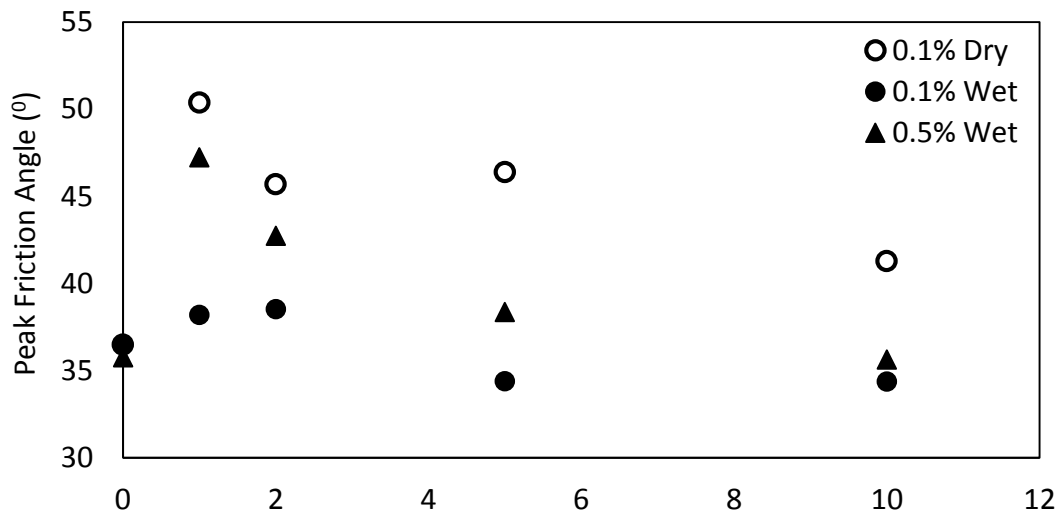
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 576 specimens at varying normal stresses (a – 1 kPa, b – 10 kPa, c – 30 kPa). Note that all three sub-figures have a split y-
 577 axis to better display the specimen data after drying cycles, with the divide between the two graph portions indicated
 578 by a horizontal dashed line.



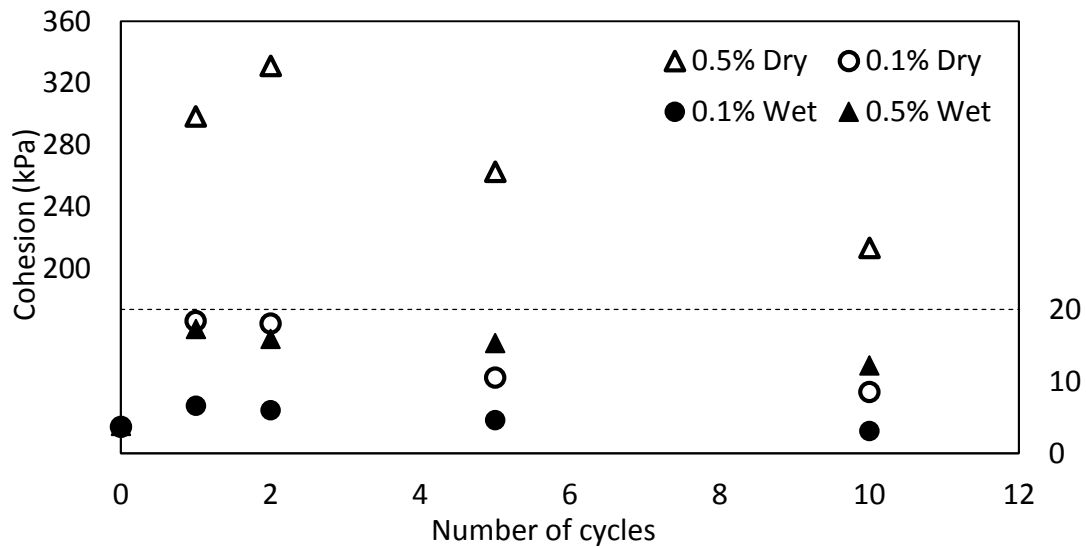
579

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

582



583 a)



584 b)

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

589