

Surface-erosion behaviour of biopolymer-treated soils assessed by EFA

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Exocultured biopolymers are ecofriendly soil-stabilisation agents with superior particle bonding, hydrogel-formation characteristics and zero endoculture duration. However, the use of exocultured biopolymers for enhancing soil resistance against surface erosion by water flow is yet to be investigated. Using erosion function apparatus (EFA) in combination with an ultrasonic P-wave reflection monitoring device, the effect of exocultured biopolymers on the erosion parameters of critical shear stress and the erodibility coefficient was examined in this study in soils with different particle distributions. In this way, biopolymer soil treatment showed a ten-fold increase in critical shear stress along with a 90% reduction in erodibility coefficient; results which could be attributed to enhanced particle-to-particle contact and increased pore-fluid viscosity and pore clogging. The results of this study demonstrate the feasibility of using exocultured biopolymers in mitigating surface erosion of erosion-prone soils.

KEYWORDS: erosion; ground improvement; soil stabilisation

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NOTATION

a	empirical exponent
k_d	erodibility coefficient (mm/h)/Pa
M	soft marine soil
m_b/m_s	biopolymer to soil content in mass (%)
S	silica sand
SK	90% silica sand–10% kaolinite mixture
z	erosion rate (mm/h)
τ	shear stress (Pa)
τ_c	critical shear stress (Pa)

INTRODUCTION

Soil scouring and erosion induced by flowing water tend to alter the stability of geotechnical engineering structures (Shirole & Holt, 1991; Pagán-Ortiz, 1998; Briaud *et al.*, 2001). In general, methods employed for the prevention and/or minimisation of such scouring include bed armouring (Lauchlan & Melville, 2001; Dey & Raikar, 2007), flow alteration (Zarrati *et al.*, 2006; Deng & Cai, 2010; Heidarpour *et al.*, 2010) and chemical soil stabilisation (Bahar *et al.*, 2004; Cheng & Cord-Ruwisch, 2012).

Recently, microbial biopolymers have been introduced to enhance geotechnical properties such as compressive

(Chang & Cho, 2012; Chang *et al.*, 2015a, 2015b) or shear strengths (Nugent *et al.*, 2010; Lee *et al.*, 2017, 2019; Chang & Cho, 2019; Kwon *et al.*, 2019) and/or reducing the hydraulic conductivity of soils (Bouazza *et al.*, 2009; Wiszniewski & Cabalar, 2014; Chang *et al.*, 2016a; Kim *et al.*, 2019). Compared to endocultured biopolymers, exocultured biopolymer soil treatment (BST) offers several benefits in terms of quantity, quality control and immediate soil stabilisation (Chang *et al.*, 2016b, 2018). However, while endocultured biopolymers have demonstrated a capacity for enhancing erosion resistance (Ham *et al.*, 2016, 2018), the erosion behaviour of exocultured biopolymer-treated soil (BPTS) remains poorly understood.

To address this, the current study investigates the effects of two exocultured biopolymers – xanthan gum (XG) and starch – on the erosion resistance of soils. Despite XG provides lower erosion resistance improvement than guar gum (Nugent *et al.*, 2010), XG is more economically feasible due to its microbial producibility (Chang *et al.*, 2016b). In-laboratory experiments were performed using erosion function apparatus (EFA) in combination with P-wave reflection monitoring. Soil erosion rates were measured under different shear stresses, and the erosion parameters of critical shear stress and erodibility coefficient were evaluated.

MATERIALS AND METHODS

Materials

Soil samples. The soil samples used in this study were variously constituted of silica sand (Pyungchang, Korea), kaolinite clay (Bintang, Indonesia) and soft marine soil (Yeosu, Korea). Figure 1 depicts the particle-size distribution, particle shape and basic properties – Atterberg limits, specific gravity and soil type – of the soils according to ASTM D 2216-10 (ASTM, 2010), D 6913/D 6913M-17 (ASTM, 2017a), D 854-14 (ASTM, 2014) and D 7928-17 (ASTM, 2017b).

Biopolymers. XG is a polysaccharide biopolymer found in the bacterial species *Xanthomonas campestris*. It is capable of strengthening soils by way of inter-particle bonding (Chang *et al.*, 2015a), and it can also facilitate permeability

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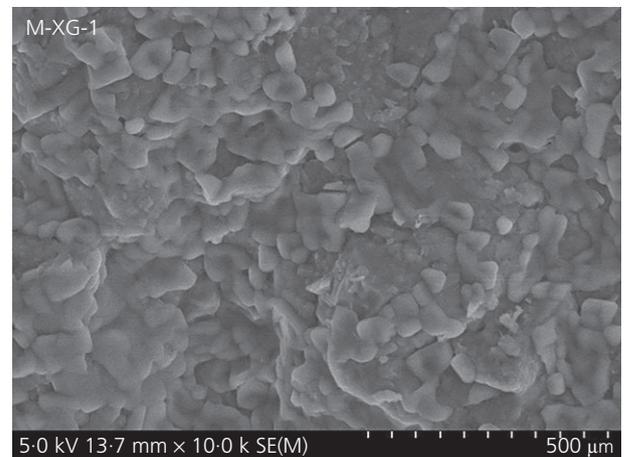
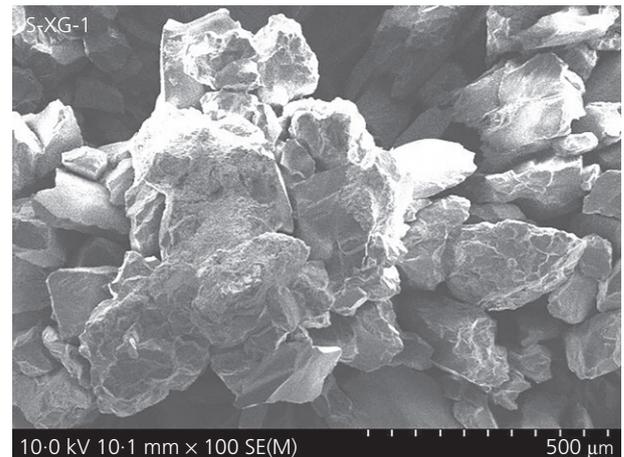
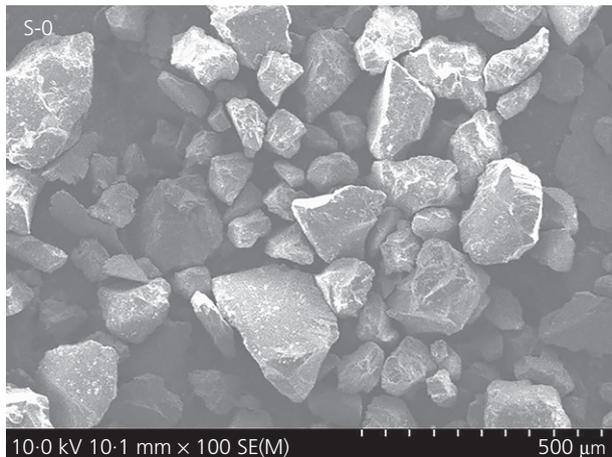
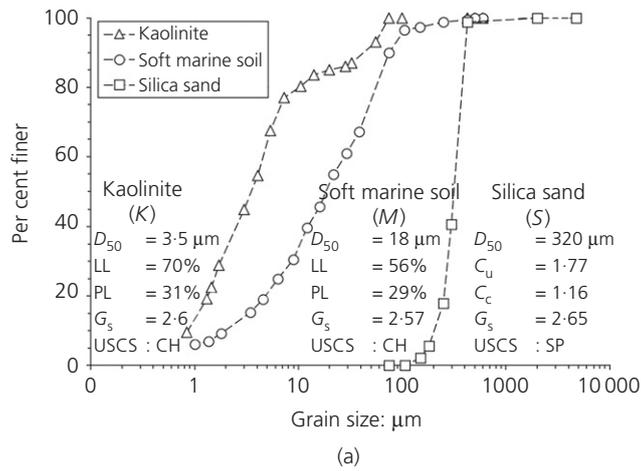


Fig. 1. Soils used in this study: (a) Particle-size distribution curve of silica sand, kaolinite and soft marine soils. SEM images of (b) untreated silica sand; (c) 1%-XG-treated silica sand; (d) untreated soft marine soil; and (e) 1%-XG-treated soft marine soil. USCS, Unified Soil Classification System

control through pore clogging (Ayeldeen *et al.*, 2016). Research-grade XG (Sigma Aldrich, CAS: 11138-66-2) was used in this study.

Starch, a biopolymer originating in plants such as potato, maize and cassava, is common and economically viable (López *et al.*, 2004; Jose & Carvalho, 2011). In geotechnical engineering applications, starch has been used to realise soil strength and viscosity control of drilling fluids (Chang *et al.*, 2016b). Research-grade corn starch (Sigma Aldrich, CAS: 9005-25-8) was used in this study.

Mixing starch with XG serves to enhance the viscosity and stability of starch gels (Shalviri *et al.*, 2010). As such, an XG–starch mixture with mass ratio of 3:7 (XS) was adopted. The results obtained were compared with pure XG-treated conditions.

Experimental methods

Sample preparation. Three soil types were considered in this study: silica sand (S); 90% silica sand with 10%

kaolinite (SK); and soft marine soil (M). All soil samples were washed and dried for 24 h in an oven at 110°C (ASTM, 2010). The dry soils and two biopolymer solutions were thoroughly mixed with controlled water content

to obtain uniform BPTS samples with intended biopolymer content (m_b/m_s). Details of specimen preparation conditions, m_b/m_s and sample identifiers are summarised in Table 1.

Table 1. Description of soil specimens

Soil	Treatment	m_b/m_s : %	Water content: %	Symbol	Void ratio	Relative compaction: %
Silica sand	Untreated	0	30	S-0	0.89	86
	XG	1	30	S-XG-1	0.90	88
	XS (30 : 70)	1	30	S-XS-1	0.90	85
Silica sand (90%)–kaolinite (10%)	Untreated	0	30	SK-0	0.85	85
Soft marine soil	Untreated	0	50	M-0	1.49	84
	XG	1	50	M-XG-1	1.62	80
	XG	2	50	M-XG-2	1.58	81

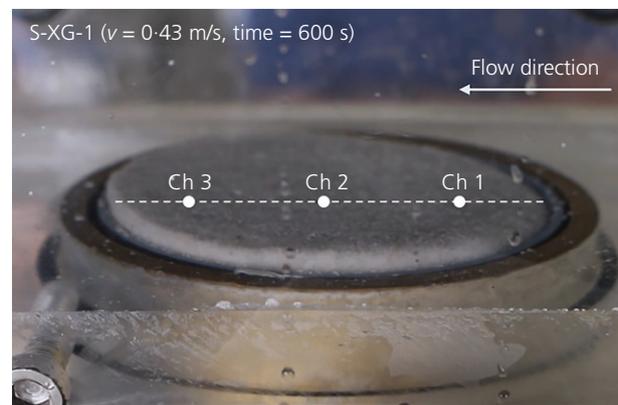
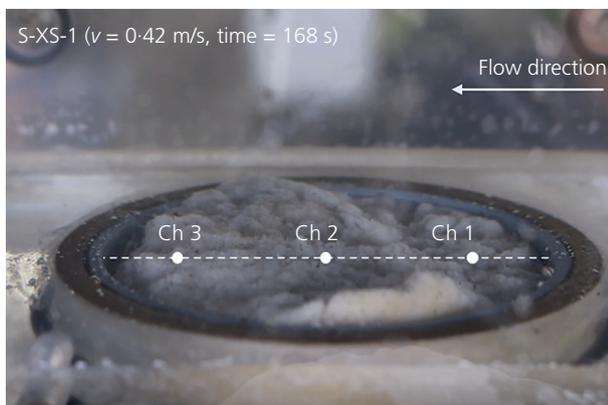
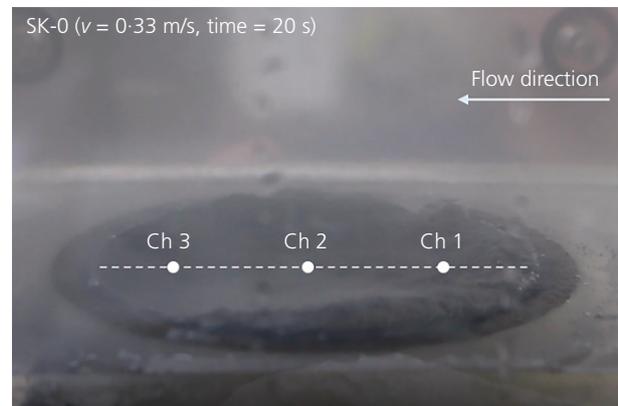
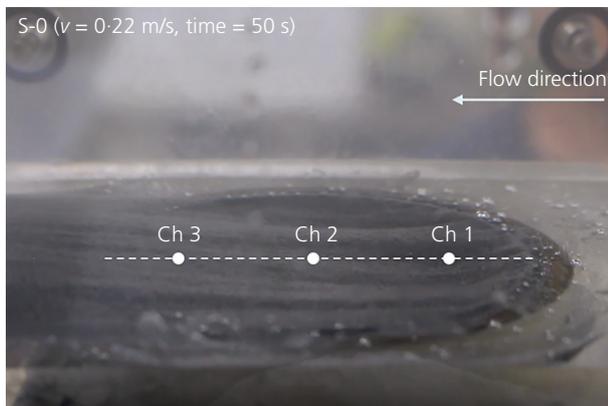
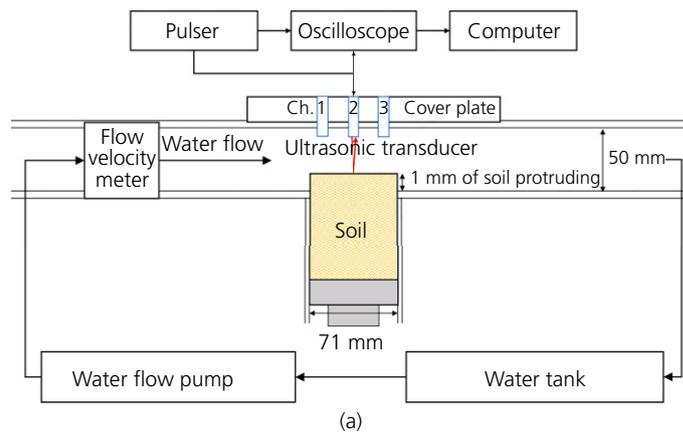


Fig. 2. Details of (a) the testing apparatus and result of EFA experiments for (b) untreated silica sand (S-0); (c) untreated silica sand–kaolinite mixture (SK-0); (d) 1% XS-treated silica sand (S-XS-1) and (e) 1% XG-treated silica sand (S-XG-1). Ch, channel

The soil mixtures were hand-tamped into thin-walled tubes that measured 300 mm long and with external and internal diameters of 76.2 and 71 mm, respectively. Soil columns of 200 mm (Ham *et al.*, 2016) were thus formed, and both ends of the tube were sealed with paraffin (Parafilm M, Sigma Aldrich, Inc.) to prevent water evaporation prior to loading for erosion testing.

Scouring tests. The soil erosion rates at various flow velocities were monitored using an ultrasonic P-wave reflection monitoring system installed on EFA (Ham *et al.*, 2016). The samples were placed inside the EFA and then subjected to water flowing at velocities ranging from 0.1 to 1.75 m/s. Once steady flow had been established and the soils fully saturated, each soil column was pushed upwards by pneumatic piston to protrude by 1 mm into the flowing water (Briaud *et al.*, 2001).

The eroded depth over time of soil was monitored using three pairs of ultrasonic transducers (VP-3, CTS Valpey Co.) to acquire P-waves reflecting from the sample surface (Ham *et al.*, 2016). Figure 2 depicts the untreated soil (a, b) and BPTS (c, d) results, demonstrating uneven surface erosion and emphasising the need for multi-channel monitoring. The time required to erode 1 mm of soil protruding from the tube was obtained by averaging the times recorded at three locations along the flow direction. To ensure repeatability, three identical specimens were prepared and tested under identical conditions. The results of P-wave monitoring demonstrated a significant increase in erosion depth with increased flow velocity, whereas reduced erosion was observed in the presence of clay and in biopolymer-treated silica sand (Fig. 3). Test results were compared with the erosion behaviour of dextran (produced by *Leuconostoc mesenteroides*)-treated sand which has been assessed using the same EFA as this study (Ham *et al.*, 2018).

EXPERIMENTAL RESULTS

Variations in erosion rate with changes in water flow

Figure 4 depicts changes in the \dot{z} of the soil samples against flow velocity. For the untreated soils (S-0, SK-0 and M-0), the \dot{z} was observed to reduce with the increase in the proportion of fine particles due to the enhanced electrostatic attraction between them so that $S-0 < SK-0 < M-0$ in terms of \dot{z} . This enhanced electrostatic attraction also served to improve resistance against flow-induced shear forces, a finding that agrees with studies by Briaud *et al.* (1999) and Ham *et al.* (2016). In addition, regardless of soil type, BST caused a reduction in the rate of soil erosion. The S-XG-1 and S-XS-1 soils were seen to withstand water flow longer than SK-0, implying that even minimal biopolymer treatment (e.g. 1% mass fraction) is sufficient to induce significant improvement in the erosion resistance of sand. Realisation of lower or even equivalent erosion mitigation using clay treatment would require an in-soil clay concentration of more than 10%.

Effect of biopolymers on erosion curve

The \dot{z} and erosion resistance of soils can be expressed in terms of shear stress (τ) caused by flowing water at the soil–water interface, and this stress can be calculated as a function of flow velocity (e.g. Reynolds number) and soil-surface roughness (Moody, 1944; Briaud *et al.*, 1999, 2001). In this study, the relationship between \dot{z} and τ was modelled in terms of critical (τ_c) and excess shear stresses (Hanson & Cook, 2004; Wan & Fell, 2004; Daly *et al.*, 2013; Khanal *et al.*, 2016) as

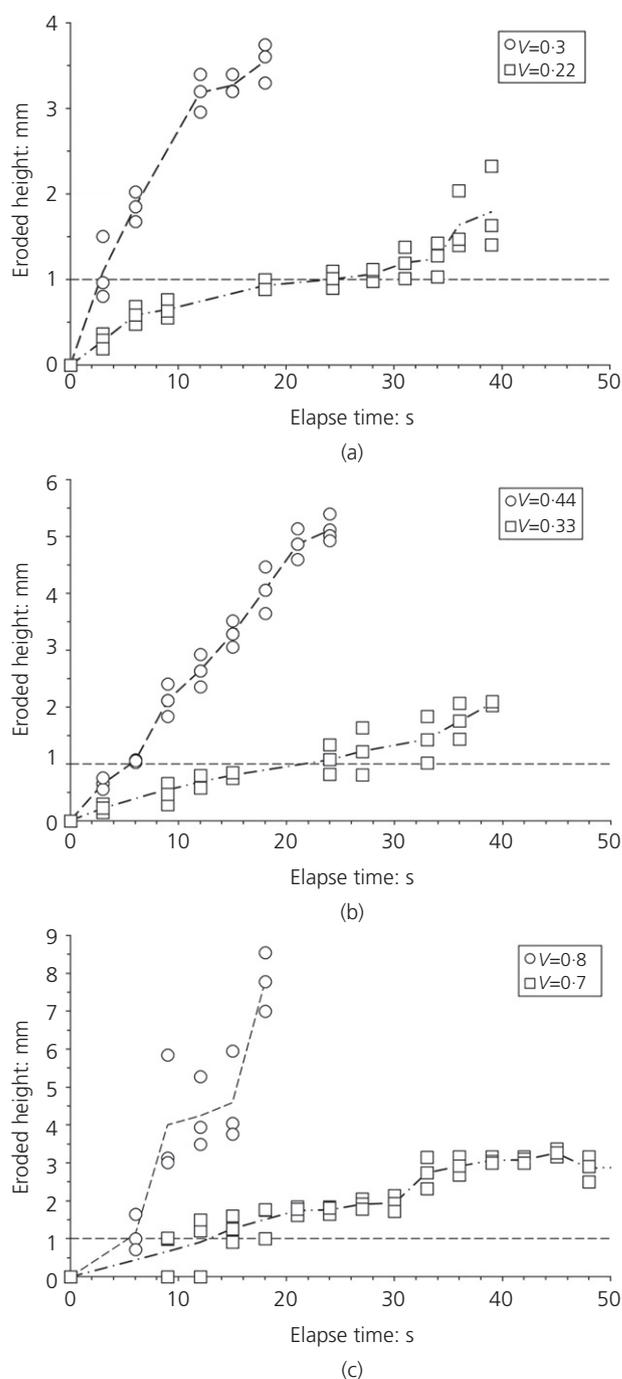


Fig. 3. Ultrasonic reflection monitoring results of S-0, SK-0 and S-XG-1 soils eroded at various flow velocities (0.22–0.8 m/s) by EFA testing

$$\dot{z} = k_d(\tau - \tau_c)^a \quad (1)$$

where k_d denotes the erodibility coefficient (mm/h Pa), indicating the sensitivity of \dot{z} to excess shear stress (Ham *et al.*, 2016), and τ_c denotes the critical shear stress (Pa) under which soil erosion from flowing water commences (Briaud *et al.*, 1999). The value of the empirical power exponent (a) was determined to be 1, and this finding was in agreement with extant studies (Hanson & Cook, 2004; Midgley *et al.*, 2012; Al-Madhachi *et al.*, 2013).

Figure 5 depicts erosion (\dot{z} - τ) curves corresponding to all untreated and the treated S and M soils. The higher the fine-particle content in untreated soils (Fig. 5(a)), the higher the erosion resistance (Briaud *et al.*, 1999, 2001;

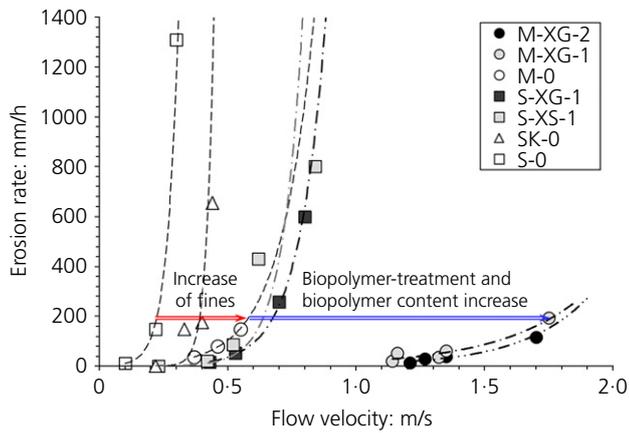


Fig. 4. Erosion rate against flow velocity

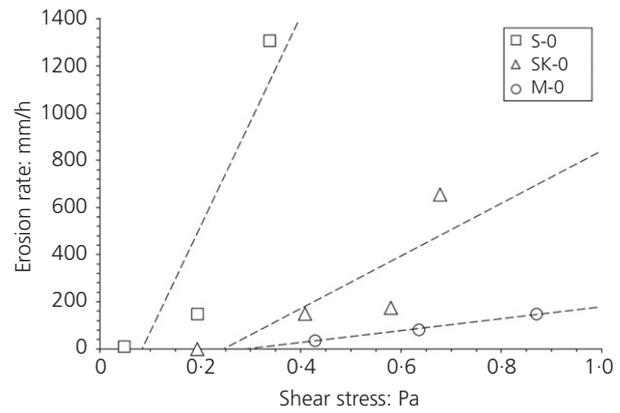
Wan & Fell, 2004; Briaud, 2008; Ham *et al.*, 2016) which can, as before, be attributed to the electrostatic attraction exerted by the increasing numbers of clay particles (Simon & Collison, 2001; Julian & Torres, 2006). Furthermore, the value of τ_c increases from 0.08 to 0.29 Pa in the order of $S-0 < SK-0 < M-0$, and soil composition was also observed to affect soil erodibility leading to a reduction in k_d values with the increase in fine particles following an $S-0 > SK-0 > M-0$ pattern (Table 2).

The BST demonstrated significant enhancement of the erosion resistance of the S and M soils (Table 2; Figs 5(b) and 5(c)). Although endocultured 0.4% dextran (Ham *et al.*, 2018) demonstrated similar resistance to that of the SK soil (Fig. 5(b)), the exocultured BSTs with 1% XG and 1% XS in this study demonstrated a significant increase in the τ_c of S soils up to 0.75 Pa (S-XG-1), as well as reducing k_d from 4465.6 to 379.9 mm/h Pa in the S-0 and S-XG-1 samples, respectively.

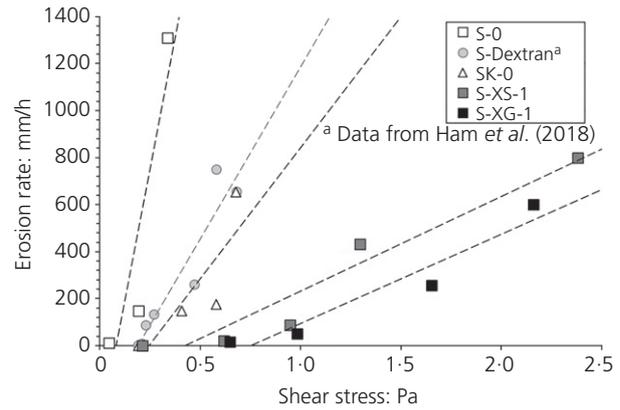
Compared to the S soil results, the erosion curves of the treated M samples indicate an even more dramatic improvement in erosion resistance (Fig. 5(c)) which could presumably be due to electrostatic interactions between clay particles and the biopolymers (Chang *et al.*, 2019). Specifically, XG treatment was observed to enhance the τ_c value in the M soils from 0.29 Pa (M-0) to 2.99 Pa (M-XG-2) while decreasing the corresponding k_d values from 252.6 mm/h Pa for M-0 to 36.9 mm/h Pa for M-XG-2 (Table 2). However, M-XG-2 only showed a minor increase of erosion resistance compared to M-XG-1 indicating that a biopolymer content of 1% is sufficient to mitigate erosion of the M soil.

Possible biopolymer mechanisms impacting erosion behaviour of soils

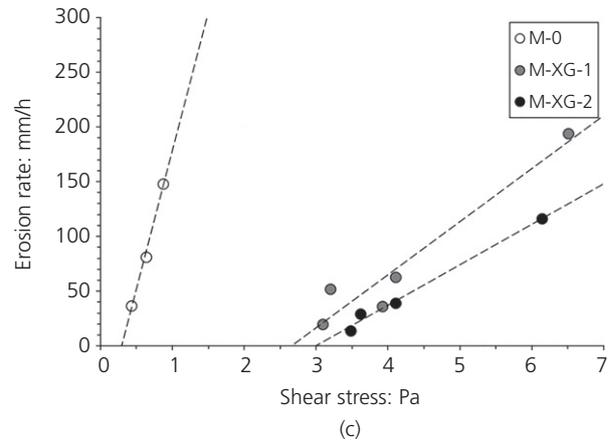
The results of this study show that adding the biopolymers XG and XS to soils enhances their erosion resistance. This can be explained in terms of three possible mechanisms pertaining to particle contact and pore space: First, including biopolymers affects the bonding characteristics of soil grains because biopolymers tend to coat and bridge soil particles by way of electrical bonding (Chang *et al.*, 2019; Renault *et al.*, 2009) and/or biofilm formation (Khatami & O'Kelly, 2012; Chang *et al.*, 2015a, 2016a). As a result, the number of shear stress cycles required to break contact between soil particles increases during BST (Briaud *et al.*, 1999, 2001). Second, biopolymers adsorb water and form hydrogels, thereby increasing pore-fluid viscosity (Matsuoka *et al.*, 1997; García-Ochoa *et al.*, 2000), and



(a)



(b)



(c)

Fig. 5. Erosion curves of the tested soils: (a) untreated soils; (b) treated silica sands and (c) treated soft marine soils

this water-adsorbing characteristic increases soil shear strength (Nugent *et al.*, 2009) and resistance to water flow (Briaud *et al.*, 2001). Finally, biopolymer-associated hydrogels reduce soil permeability and cause pore clogging (Martin *et al.*, 1996), which leads to a reduction in seepage flow and surface erosion (Ham *et al.*, 2018). The combined effect of these phenomena is that the addition of biopolymers serves to increase the shear stress (τ_c) at which erosion occurs while also reducing the amount of erosion due to water flow (k_d) (Table 2 and Fig. 5).

BPTS strength gradually reduces with cyclical wetting and drying processes (Chang *et al.*, 2017). This study was conducted in fully saturated conditions, but matric suction in unsaturated conditions may further enhance the erosion resistance of soils (Shaikh *et al.*, 1988; Vanapalli *et al.*, 1996). Thus, it is recommended that the long-term durability of

Table 2. EFA test results

Soil	BST condition	Symbol	Fine content: %	m_b/m_s : %	k_d : mm/h	τ_c : Pa
Silica sand	Untreated	S-0	0	0	4465.6	0.08
	Kaolinite (10%)	SK-0	10	0	1116.2	0.25
	Dextran (0.4%)*	S-Dextran	0	0.4	1464.8	0.19
	XS (1%)	S-XS-1	0	1	403.0	0.43
	XG (1%)	S-XG-1	0	1	379.9	0.75
Soft marine soil	Untreated	M-0	95	0	252.6	0.29
	XG (1%)	M-XG-1	95	1	48.5	2.65
	XG (2%)	M-XG-2	95	2	36.9	2.99

*Data from Ham *et al.* (2018).

BPTS and the effects of unsaturated conditions are considered in further studies.

CONCLUSIONS

This study demonstrates the effects of exocultured biopolymer treatment on the erosion resistance of soils and confirms that their addition improves erosion resistance by enhancing interparticle bonding, increasing fluid viscosity, and inducing greater pore clogging. The addition of a small amount of biopolymer (~1% aggregate mass) facilitates higher erosion resistance than other treatments, for example, the addition of kaolinite (which may require up to 10% aggregate mass) or endocultured dextran. This demonstrates the potential of exocultured biopolymer treatments for improving the erosion resistance of different soils. In future work, variations in the erosion parameters – critical shear stress and erodibility coefficient – will be quantified in terms of biopolymer type and content, and the physico-chemical characteristics of soils. Indeed, the long-term durability of BPTS must be verified under severe climatic variation to ensure its in situ performance and stability.

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