Soil – water characteristics of xanthan gum biopolymer containing soils

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ABSTRACT: Today there is an increasing number of biopolymer applications for environment-friendly soil improvement and erosion prevention. For lower cost and human safety, biopolymers with agar, guar, xanthan, casein, gellan, and sodium alginate have been commonly studied to improve strength and to decrease the hydraulic conductivity of highly permeable soil materials. Among those, xanthan gum is known to perform better in terms of lowering permeability. The objective of this study is to investigate the effects of xanthan gum on the relationship between suction and volumetric water content of bio-treated soil. Furthermore, it is possible to quantify the accurate water-entry value, which is the threshold boundary for water infiltration into soils. For these purposes, a series of column tests were conducted on pure sand, artificial clayed sand, and xanthan-treated soil with varying xanthan content (0.5, 1, and 2%) to obtain the soil water characteristic curve for adsorption. Tubes 100 mm in diameter and 500 mm in length were used for this study. The soils were compacted into the tubes at a target dry density before being placed in a water tray. Water rose up due to capillary force from the bottom of the tubes. The experiment was ended when the water rising in the tube reached the equilibrium.

KEYWORDS: xanthan gum, bio-clogging, absorption ability, capillary conductivity, SWCCs.

1 INTRODUCTION.

Biopolymers have significantly contributed to the development of different foods, medicine, and petroleum industries. For example, gellan gum is a microbial biopolymer with functional properties that are appropriate for producing liquid gels, edible films, stable drinks, gelation desserts, jam, and microencapsulated products (Hasheminya and Dehghannya 2013) and it has been successfully employed in the biomedical field as an absorbing material in wound healing and stomatology and as a cell carrier in relation to tissue engineering (Osmałek et al. 2014). Because of the high viscosity of solutions and water solubility of polymers, xanthan gum is widely used to lubricate and reduce the friction in drill-holes to enhance oil recovery processes (Garcıa-Ochoa et al. 2000).

The last decade has seen a significant growth of research on biopolymer application to geotechnical engineering, especially for soil stability and improvement purposes. Many researchers have found that biopolymers such as agar, starch, betaglucan, and xanthan can improve the strength characteristics of soil (Chang and Cho 2012; Chang et al. 2015c; Khatami and O'Kelly 2012; Smitha and Sachan 2016). For example, betaglucan treatment enhances the strength of natural soil with an increment ratio of up to 300 – 400% (Chang and Cho 2012, 2014). Furthermore, biopolymers can lend positive performance in decreasing the hydraulic conductivity of high permeability soils such as guar gum, xanthan gum, sodium alginate (Aminpour 2015; Bouazza et al. 2009), and gellan gum (Chang et al. 2016). It has also been demonstrated that chitosan provides excellent performance in water treatment (Zemmouri et al. 2013).

In addition, since biopolymers can enhance the inter-particle cohesion of soils, they show promise for effective dust control and anti-desertification. Xanthan gum and guar gum have the capability of stabilizing mine tailings for dust control. Both xanthan and guar are effective in enhancing the moisture retention capacity, improving the dust resistance, and increasing the surface strength of mine tailings beyond that of water wetting (Chen et al. 2014). Also, for instance, beta-1,3/1,6 glucan and xanthan gum enhance soil erosion resistance in the same manner, while the former treatment results in better vegetation growth than the latter. Combining biopolymers with pre-existing anti-desertification efforts on desert fronts has been suggested for the best efficiency (Chang et al. 2015c).

With regard to environmental protection, the use of biopolymers can significantly reduce CO2 emissions resulting from available conventional methods (cement) that are the source of approximately 5% of global greenhouse gases (Hendriks et al. 1998). For example, soils treated with 1% xanthan gum and 1% gellan gum show higher compressive strength levels than 10 % cement mixed soils (Chang et al. 2015b). Generally, biopolymers are recognized as a viable alternative to conventional chemical polymers because of their potential cost savings, low environment impact, non-toxicity, and non-secondary pollution (Aminpour 2015).

The hydrophilic structure of biopolymers renders them capable of holding large amounts of water. Therefore, the incorporation of a biopolymer within soils shows remarkable performance in filling the soil pores by absorbing suddenly infiltrated water and then swelling to viscous hydrogels. In other words, the existence of biopolymer strongly affects the wetting soil – water characteristics (SWC). This issue has not been paid attention in researches on biopolymer – treated soil.

In geotechnical and geo-environmental engineering practice, the SWC curves express a constitutive relationship between the water content and suction within soil (Fredlund et al. 2012). The SWC curve is known to represent the ability of soil to retain water at a certain level of applied suction. This work focuses on the wetting SWC curves, which can provide the parameters for numerical modeling of the seepage flow through unsaturated soil.

Xanthan biopolymer gum, which offers excellent performance in reducing permeability among common bio – based biopolymers (Bouazza et al. 2009), was used to treat Jumunjin sand and a Jumunjin sand – Kaolinite soil mixture. In this study, a capillary rise open tube was used to obtain the wetting SWC curve of biopolymer – treated soil. It is concluded that, due to the water absorption ability of xanthan gum, the initial volumetric water content of soil is much higher than that of the untreated soil. Bio-clogging contributes to a remarkable reduction of capillary conductivity of soil, and, in turn, causes long equilibrium time of the soils. Furthermore, hydrophilic absorption and swelling strongly depends on biopolymer concentration. Finally, the SWCC parameters of sand – clay mixtures obtained via the van Genuchten equation using non – linear fitting software (Seki 2007) show that the θr, α, and n values of the treated and untreated soil are almost the same. The effects of hydrophilic absorption and bio-clogging on the water entry value of soil are shown by the significant increase of the water content of the bio-treated soil at lower suction compared to untreated soil.

2 MATERIALS AND EXPERIMENTAL METHODS

2.1 *Materials*

2.1.1 *Sand*

Jumunjin sand is a standard sand in Korea. The sand properties are shown in Table 1. Figure 1 shows the wetting SWCC of Jumunjin sand. The data were compared with medium and fine sand data (Yang et al. 2004). The SWCC data were fitted by the van Genuchten equation, and the parameters are also summarized in Figure 1.

Table 1. Basic properties of jumunjin sand

Unified Soil Classification System		SP
Specific gravity, Gs	[-]	2.65
Particle-size analysis results		
D_{60}	[mm]	0.50
D_{30}	[mm]	0.37
D_{10}	[mm]	0.36
Coefficient of uniformity, Cu	[-]	1.39
Coefficient of curvature, Cc	[-]	0.76

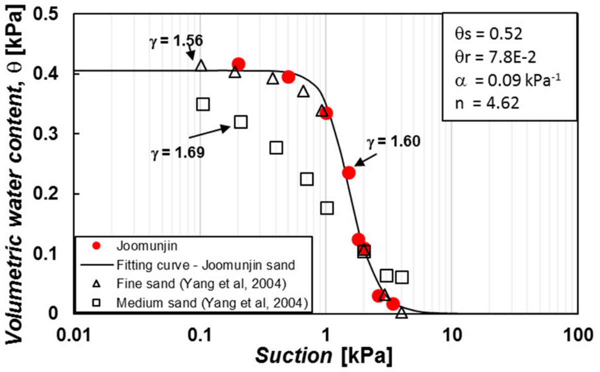

Figure 1. Wetting SWCC of Jumunjin sand

2.1.2 *Sand – Clay mixture*

For fine soil, kaolinite, which is known as the most common (Murray 2000) and non-swelling clay mineral in soil (Osacky et al. 2015), was used. The specific gravity is 2.65 and the mean grain size is 0.044. The clay powder is mixed with Joomunjin sand with a ratio of clay to sand at 2:8.

2.1.3 *Xanthan*

Xanthan gum (CAS No.11138-66-2) was used to represent a high molecular chain type and gel (gum) - forming type biopolymer. The xanthan gum structure consists of repeated units formed by five sugar residues: two glucose, two mannose, and one glucuronic acid (Figure 2) (Jansson et al. 1975; Melton et al. 1976). Detailed physical properties of xanthan gum can be found in previous studies (Chang et al. 2015a; Takahashi et al. 2006). Xanthan gum shows the greatest efficiency with well graded soils with fine particles (Chang et al. 2015a; Chenu 1993; Martin 1971). It also has a best performance in decreasing the hydraulic conductivity of silty sand soil (Bouazza et al. 2009). For a hydrophilic colloid to thicken and stabilize water-based suspensions, xanthan gum has been used in the oil drilling industry to thicken drilling fluids, which improves drilling effectiveness.

2.2 *Experimental methods*

2.2.1 *Specimen preparation*

Table 2 summarizes soil types and biopolymer concentration used to treat the soils. First, a xanthan hydrogel solution was prepared by dissolving xanthan gum powder into distilled water at room temperature (25°C) according to the target biopolymer concentration, which is relative to the mass of the soil. The initial water content for mixing was set at 10% of the dry soil weight. The xanthan gum – soil mixtures were dried in an oven at 30°C.

Table 2. Dry density of the treated and untreated soils

Soil	Dry density (g/cm^3)		
	Untreated	0.5% treated	1.0% treated
Jumunjin sand	1.6	1.54	1.46
Sand – 20% Kao	1.55	1.55	1.50

2.2.2 *Wetting SWCC test*

The wetting SWCCs can be obtained using a capillary rise open tube (Fredlund et al. 2012). Tubes with 50 cm height and 10 cm diameter were used (Figure.3). The soil is compacted into an open tube and placed in a tray. Water is then poured to fill the tray at the bottom of the tube. The water from the tray subsequently starts to move into the soil. The presence of water is always maintained during the test. To prevent evaporation, the top of the tube is covered.

The height of a soil specimen above water level is assumed to be the negative pore – water pressure head at that point. The matrix suction ($u_a - u_w$) at that point can be expressed as follows (Fredlund et al. 2012; Yang et al. 2004)

$$u_a - u_w = \rho_w.g.H \quad (1)$$

where u_a is the pore - air pressure, u_w is the pore - water pressure, ρ_w is the density of water (1.0 g/cm^3), g is the acceleration due to gravity (m/s^2),and H is the height of water within the column soil (m).

The volumetric water content of soil was calculated using the following equation:

$$\theta_w = (\rho_d/\rho_w).w \quad (2)$$

where w is the gravimetric water content and ρ_d is the dry density of soil.

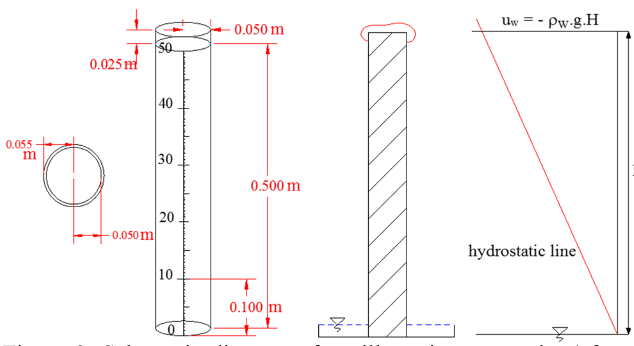

Figure 3. Schematic diagram of capillary rise open tube (after Yang et al., 2004)

3 RESULTS AND DISCUSSIONS

3.1 *Reduction of capillary conductivity of soils*

Figure 4 shows the reduction in the capillary conductivity of sand due to xanthan gum. The biopolymer affects the capillary mechanisms with respect to soil types since the types of bonding between biopolymer xanthan gum and soil particles are different.

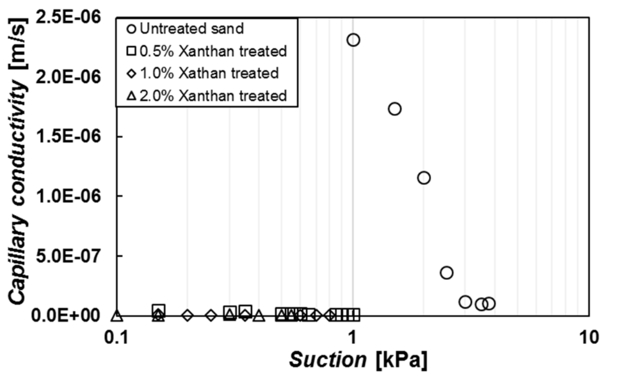

Figure 4. Capillary conductivity of treated and untreated sand

For pure sand, continuous biopolymer matrix which form and enhance inter-particle bonds between sand particles (Chang et al. 2015a), immediately absorbed water when water is supplied. The swelling of the biopolymer hydrogels fill to pores and prevents upward flow of water. Until the viscosity of the biopolymer matrix becomes sufficiently low, the water could diffuse. Therefore, higher biopolymer content was used, and lower capillary conductivity could be obtained. On the contrary, the rising mechanism of water within the untreated sand is based on surface tension.

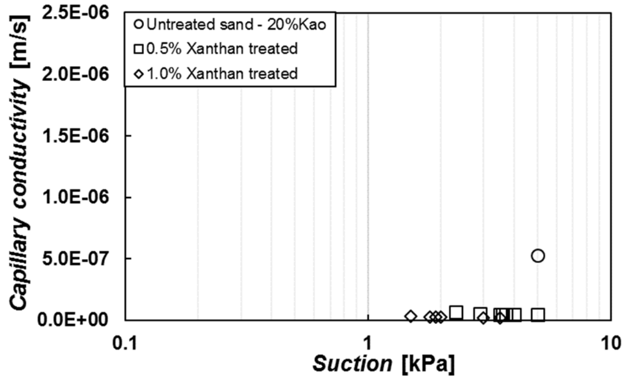

Figure 5. Capillary conductivity of the treated and untreated sand – 20% Kaolinite

In the case of the sand – 20% kaolonite mixture, indirect bonding between sand particles and xanthan gum and direct bonding via hydrogen or electrostatic bonding between clay particles and xanthan gum formed (Chang et al. 2015a). The xanthan – clay matrixes contact with sand via xanthan thread around the sand particle surface or are free within the soil. When the treated soil contacted water molecules, kaolinite particles and xanthan gum immediately absorbed water. Although, pores are clogged with xanthan gum hydrogels, presence of kaolinite particles allows water to slowly rise along their surface double layers. For the untreated sand – clay mixture, the reduction in capillary rise within the untreated sand – kaolinite mixture is solely because of the wetting process of kaolinite.

3.2 *SWCCs of biopolymer treated soil*

The aforementioned effects of bio-clogging on the capillary conductivity of soils caused long equilibrium time of the soil during the wetting test. Table 3 summarizes the current suction and the equivalent time of the specimens. When the capillary tube of sand – kaolinite soil was allowed to wet for 11 days, it took 122 days to reach the same height of wetting for 0.5% xanthan.

As can be seen from Figure 6, xanthan gum causes the soil to absorb more water, and consequently the volumetric water content of the treated soil was higher compared to that of the untreated soil at low suction. However, at higher suction, the obtained volumetric water content was lower than that of the untreated soil. It is believed that the combination of simultaneous absorption and bio-clogging of the biopolymer and the existence of kaolinite which allows minor upward flows even most pores are fully clogged with biopolymer hydrogels.

Furthermore, the water entry value of the treated soil ($\psi_{w(b)}$ = 3.6) was slightly lower than that of the untreated soil (ψ_w = 4.85). This demonstrated the effects of the water holding ability of xanthan gum and its bio-clogging property on the suction threshold where the water content of soil increases significantly. There were no significant differences in values of θ_r, α, and n for treated and untreated soils.

Table 3: Suction and equivalent time

Specimens		Density [g/cm^3]	Current suction [kPa]	Time [days]
Types of soil	Biopolymer content [%]			
Sand	0	1.60	3.75	42
	0.5	1.54	0.10	150
	1.0	1.46	0.80	151
	2.0	1.47	0.55	142
Sand – 20% Kao	0	1.55	**5.00**	**11**
	0.5	1.55	**5.00**	**122**
	1.0	1.50	3.50	183

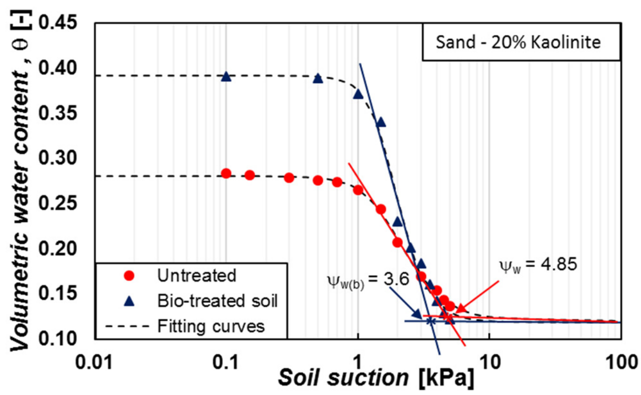

Figure 6. The wetting SWCC of the treated and untreated sand – 20% Kaolinite

Table 4 Van Genuchten parameters

Parameters	Untreated	Treated
α	0.547	0.555
n	3.076	4.086
m	0.674	0.755
θ_s	2.8e-1	3.9e-1

θ_r	1.2e-1	1.2e-1

4 CONCLUSIONS

Using a capillary rise open tube, the wetting SWCC of xanthan - treated soil was estimated. From the experimental data, the following conclusions can be drawn:

- Xanthan gum shows a strong effect on the movement of upward flow within the soil column due to its extremely high water absorption ability. This effect significantly depends on the biopolymer concentration and viscosity.

- The water rising mechanism within xanthan treated sand is due to water diffusion via low viscosity of biopolymer hydrogel, and within a xanthan treated sand – clay mixture is due to the wetting clay bridges and water diffusion via low viscosity of the biopolymer hydrogel.

- The wetting SWCC of 0.5% xanthan treated sand – 20% Kaolinite verified the effects of hydrophilic absorption and bio – clogging of xanthan gum on the water entry value of soil. Water content of the bio-treated soil increases significantly at lower suction compared to untreated soil.

- Since the xanthan gum caused long equilibrium time of the soils, the use of a capillary rise open tube is not an appropriate method to obtain the wetting SWCCs for biopolymer treated soil.

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