Upward Wetting Behavior of Unsaturated Xanthan Gum–Treated Sand

An T. P. Tran[1]; Ilhan Chang, Ph.D., A.M.ASCE[2]; Jooyoung Im[3];
and Gye-Chun Cho, Ph.D., M.ASCE[4]

[1]Graduate Student, Dept. of Civil and Environmental Engineering, KAIST, Daejeon 34141, South Korea. E-mail: phuongan313@gmail.com
[2]Graduate Student, Dept. of Civil and Environmental Engineering, KAIST, Daejeon 34141, South Korea. E-mail: jooyoungim@kaist.ac.kr
[3]Lecturer, School of Engineering and Information Technology, Univ. of New South Wales, Canberra, ACT 2600, Australia. E-mail: ilhan.chang@unsw.edu.au
[4]Professor, Dept. of Civil and Environmental Engineering, KAIST, Daejeon 34141, South Korea. E-mail: gyechun@kaist.edu

Abstract

Biopolymer-soil treatment shows high potential to be used in various geotechnical engineering practices. Previous studies show appropriate performance of biopolymer on soil strength improvement and hydraulic instability reduction. In this study, the capillary conductivity of biopolymer-treated soils is investigated via laboratory testing. A mini column (3.5 cm diameter and 10 cm height) approach was used. Xanthan gum-treated soils were compacted into the columns and dried before wetting. The columns were then partially wetted from the bottom to induce upward wetting via hydrophilic adsorption and capillarity. Depending on soil types, effects of xanthan gum hydrogel concentration on capillary conductivity of soils was different. Direct water flow via capillary rise is restricted, while diffusion through hydrogels seems to become the dominant path in sand. Meanwhile, xanthan gum concentration could decide an increase or decrease in capillary conductivity within clayey soil.

INTRODUCTION

In agriculture, the capillary rise of water from ground water level and water retained within soils after a rainfall or an irrigation are the main water supply sources for the plants. In geotechnical engineering, capillary rise is a well-known unsaturated soil phenomenon that describes the movement of pore water from lower elevation to higher elevation driven by the hydraulic head gradient acting across the curved pore air/ pore water interface (Lu and Likos 2004).

The plants will face a drought stress if the water level is located at large depth due to the fact that the capillary conductivity of the soil is low for high/moderately high matric suction (Butijn and Wesseling 1959). Furthermore, the soil type is also an effect factor that bring the drought stress to the plants. For example, sandy soils are characterized by their lower water - holding capacity and excessive drainage of water below the root zone (Fan et al. 2005).

Previous studies have shown a significant performance of hydrophilic gels on the water retention improvement of soils, which in turn increases the survival and growth of plants. It is due to the fact that hydrophilic gels can absorb up to 400 times its mass in water (Bhardwaj et al. 2007). Hydrophilic gels used in this field are polymers (Agaba et al. 2010; Viero and Little 2006) and biopolymers (Chang et al. 2015a; Czarnes et al. 2000), and they can increase the water storage capacity in soils (Silberbush et al. 1993) and the amount of water retained under drought conditions (Al-Darby 1996; Bhardwaj et al. 2007; Chenu 1993). Bhardwaj et al. (2007) used the "ink bottle" effect and the difference in contact angle between the advancing and receding water wall menisci to explain the hysteresis of water soil characteristic curves of the treated soil under drying and wetting conditions. So far, however, there has been little discussion about the capillary mechanism within a biopolymer treated soil column.

Today, environmentally-friendly biopolymer-soil treatment shows high potential to be used in various geotechnical engineering practices. Biopolymers show appropriate performances on soil strengthening (Chang and Cho 2012; Chang et al. 2016; Smitha and Sachan 2016) and hydraulic instability reduction applications (Bouazza et al. 2009; Chang et al. 2016). Furthermore, dust or fine particle control is another great application of biopolymers (Chang et al. 2015a; Chen et al. 2014). To our knowledge, a detail of penetration mechanism of water into the biopolymer – treated soil has not been deeply considered.

Therefore, in this study the wetting and other soil-water characteristics of biopolymer-treated soils at low matric suction are investigated via laboratory testing. A mini column (3.5 cm diameter and 10 cm height) approach was used for experimental testing. Xanthan gum-treated soil (0, 0.1, 0.25, 0.5% and 1.0% to the mass of soil) was compacted into the columns and dried before wetting. The columns were then partially saturated on the bottom to induce upward wetting via hydrophilic adsorption and capillarity effects.

MATERIALS AND EXPERIMENTAL METHODS

Materials

Sand. Joomunjin sand is standard sand in Korea, which has been used in numerous studies (Chang et al. 2016; Kim et al. 2012; Yang et al. 2007). The sand properties are shown in Table 1.

Sand – Clay mixture. Kaolinite, which is classified as a non – swelling clay materials (Osacky et al. 2015), was used to present fine particles. Kaolinite powder was mixed with Joomujin sand with a sand – clay ratio of 8:2. The mixture soil is classified as clayey soil.

Xanthan gum biopolymers. Xanthan gum (CAS No.11138-66-2) was used to represent a high molecular gel (gum) - forming biopolymer. Figure 1 illustrates the xanthan gum structure that consists of repeated units formed by five sugar residues: two glucose, two mannose, and one glucuronic acid (Jansson et al. 1975). Xanthan gum has the best performance in decreasing the hydraulic conductivity of silty sand (Bouazza et al. 2009). 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).

Experimental methods

Specimen preparation. 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 (0.0%, 0.1%, 0.25%, 0.5% and 1.0% to the soil mass). The initial water content for mixing was set at 10% of the dry weight of the soil. The xanthan gum – soil mixtures were dried in an oven at 30°C.

Capillary rise open tube test. Tubes with 10 cm height and 3.5 cm diameter were used. In the capillary tube test, soil is compacted in an open tube at a target dry density and placed in an aluminum disk with a water table maintained at the bottom of the tube (Figure 2). The top of the tube is covered to prevent the evaporation. As soon as water is poured into the dish, the water starts to move into the soil.

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]	0.26
Coefficient of uniformity, Cu	[-]	1.39
Coefficient of curvature, Cc	[-]	0.76

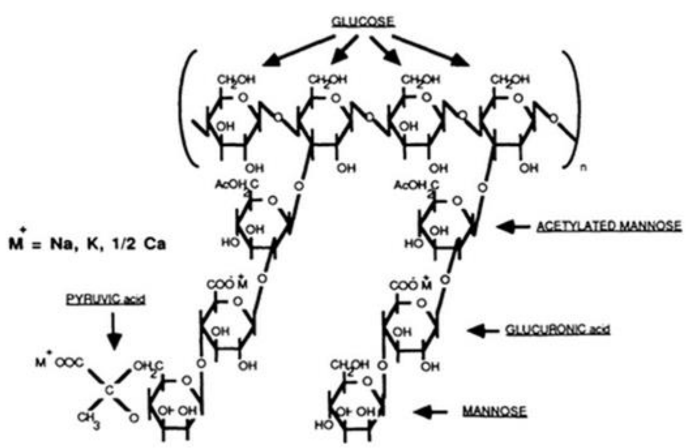

Figure 1. Structure of Xanthan gum biopolymer

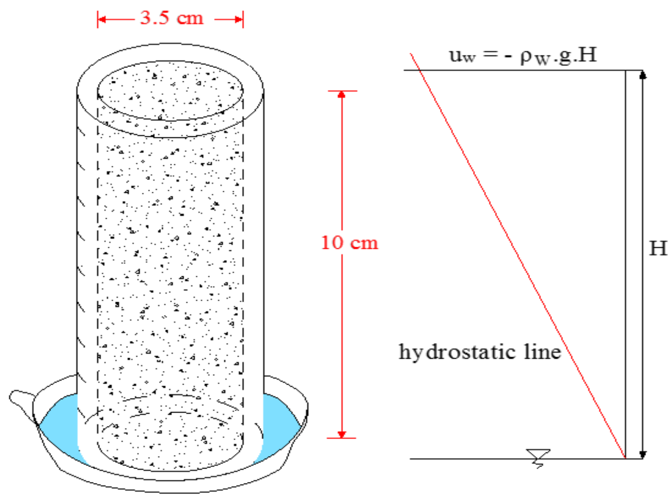

Figure 2. Schematic diagram of the capillary open tube test

The hydraulic conductivity of upward flow (i.e. capillary conductivity) is measured from a various level in the tubes. The height of a soil specimen above the water table is assumed to be equal to the capillary head at that point (Yang et al. 2004). The magnitude of the capillary head is calculated as $u_w = -\rho_w.g.H$, where ρ_w is the density of water (1 g/cm^3); g is the gravitational acceleration (≈ 10 m/s^2) and H is the height of a soil specimen above the water level (m)

RESULTS

Effects of xanthan gum concentration on capillary conductivity of soil

Figure 3 shows the change in capillary conductivity with matric suction for the biopolymer treated and untreated specimens. The results show that the presence of xanthan gum has varying effects on the capillary conductivity.

The capillary conductivity of pure sand immediately and significantly decreased as sand was treated even at 0.1% concentration (Figure 3a). The higher xanthan gum concentration within soil, the lower conductivity could be seen. Swelling and filling of pore spaces in soils as xanthan acts with water, which is known as a pore – clogging or plugging effect, are the main reasons for the reduction in conductivity of treated sand.

Meanwhile, xanthan showed different effects on conductivity of clayey soil. 0.1% of xanthan gum improved the movement of water within the treated clayey, leading to the increase in hydraulic conductivity with suction. For the 0.25% xanthan treated specimen, higher conductivity than untreated specimen could be seen at matric suctions lower than 0.6 kPa. The conductivity reduction of clayey soils were obtained when the xanthan concentration was increased to 0.5% (Figure 3b). This is due to the simultaneous combination of xanthan gum – water interaction, water – kaolinite interaction and Kaolinite – xanthan interaction.

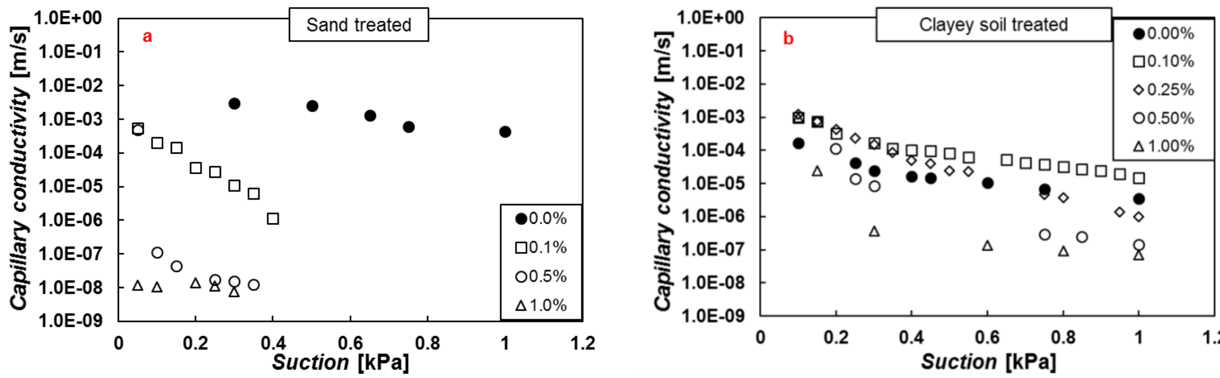

Figure 3. Capillary conductivity of xanthan treated soils. (a) Sand. (b) Clayey soil.

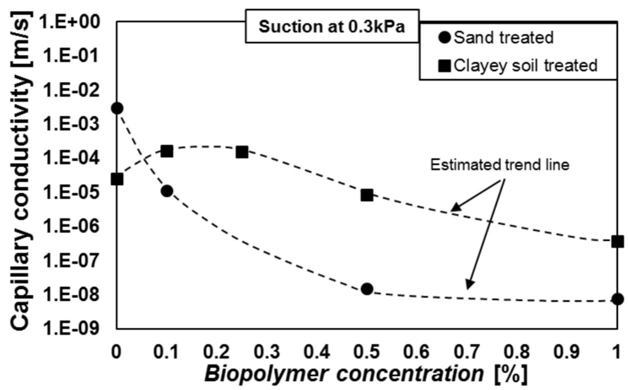

Figure 4. Effect of biopolymer concentration on capillary conductivity of varying soil types.

Soil types and xanthan gum concentration relationship

The change in capillary conductivity of soils according to xanthan gum concentration at a given matric suction of 0.3 kPa is shown in Figure 4. The effects of xanthan gum on the conductivity of the soils are affected by soil types. The capillary conductivity of xanthan gum treated sand followed a decreasing trend line from 3 x 10^{-3} to 1.5 x 10^{-8} m/s as xanthan gum concentration decreased to 0.5%. After this point however, the conductivity levels off to approximately 1 x 10^{-8} m/s.

A different line trend could be obtained in the case of the treated clayey soils. 0.1% xanthan concentration increased the capillary conductivity, while turning point could be seen as xanthan concentration increased to 0.25%. At this point the conductivity followed a decreasing trend as higher xanthan gum content was used.

DISCUSSIONS

Upward rise mechanism of water within xanthan treated soils

The xanthan gum biopolymer affects the capillary mechanism with respect to soil types since the bonding types between xanthan gum and soil particles are different. Figure 5 illustrates the effect of xanthan concentration on water movement within sand column.

For pure sand, the xanthan gel is formed around the sand particles due to the biopolymer's hydrophilic nature along with the low interaction between the xanthan biopolymers and the sand particles (Chang et al. 2015b). The swelling of biopolymer due to the absorption of water caused the upward flow to cease through clogging effects in the pore spaces. As a result of the high viscosity of xanthan solutions, a lower concentration of xanthan gum will allow for easier water diffusion compared to the higher concentration treated sands (Figure 5b & c). The capillary rise within the untreated sand is formed via surface tension (Figure 5a).

Figure 6a shows the capillary rise mechanism within clayey soil. Surface tension on sand and water absorption of kaolinite pulled the water upward. Xanthan gum and kaolinite played an important role on the water movement due to their water absorptive capacity, specifically, xanthan gum biopolymer (Figure 6b & c). Unlike the sandy soil, the xanthan gum has a higher interaction with clayey soils, and as a result, the xanthan gum biopolymers have a tendency to interact with the kaolinite particles along with the water molecules.

As can be seen from Figure 6a & b, for the lower treated clayey soils, the xanthan gum acted as additional bridges of water molecules by interacting more directly with the clay particles, which in turn led to a faster movement of water compared to untreated clayey soils. However, as higher concentration of xanthan was used, bio-clogging effects of xanthan gum dominated the pore spaces, so that water was trapped at lower suction levels. In this case the hydraulic bio-clogging effect prevailed over the capillary conductivity resulting in a halt in water movement.

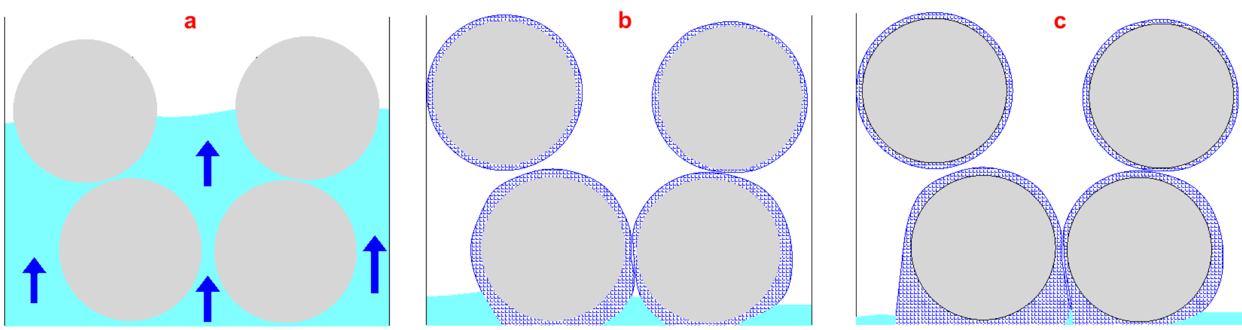

Figure 5. Water movement of xanthan gum-sand mixtures. (a) 0%. (b) 0.1%. (c) 1.0%.

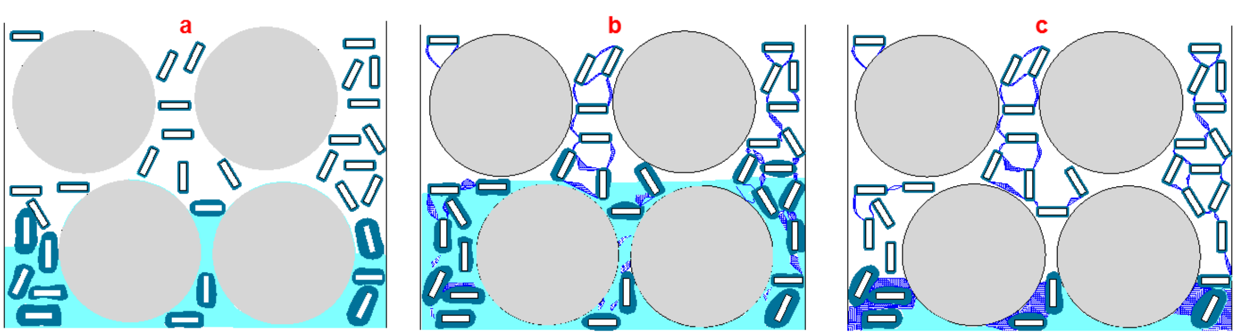

Figure 6. Upward flow of xanthan gum-clayey soil mixtures. (a) 0%. (b) 0.1%. (c) 1.0%.

Application of xanthan gum biopolymer to geotechnical engineering practice

As aforementioned, biopolymer recently has been considered as a promising friendly – environmental materials in controlling the quantity of water penetrating into soils, which can be applied to prevent the water erosion of slopes. So far, a question on an optimal amount of biopolymer which should be used to perform not only the most engineering effectiveness but also the economical effectiveness of biopolymer to where it is applied has not been solved. Results of this study show that the amount of biopolymer used strongly depends on types of soil. If the soil that need to be treated is sand, then a small amount of biopolymer such as 0.1% xanthan gum can significantly decrease the infiltration of water. Meanwhile, it is suggested that 1% of xanthan gum should be used to obtain a significant effect on reducing the infiltration rate of water within clayey soils.

CONCLUSION

A series of low suction capillary tests was conducted on xanthan gum treated soils with varying types of soils and xanthan concentration by using mini column tubes (3.5 cm diameter and 10 cm height). Some conclusions are written as follows:

1. Xanthan gum biopolymer can affect the capillary rise of the soils, which depends on soil types (sand or clayey).
2. For lower xanthan treated clayey soils, xanthan works as bridges to improve the capillary conductivity. The significant control in water movement is observed for 1.0% xanthan gum treatment conditions.
3. 0.1% xanthan biopolymer can perform a perfect effectiveness on reduction of capillary hydraulic of sand.

For further study, the capillary conductivity of xanthan treated sand soil should be considered.

ACKNOWLEDGEMENT

The research described in this paper was financially supported by a grant (17AWMP-B114119-02) from the Water Management Research Program funded by the Ministry of Land, Infrastructure, and Transport (MOLIT) of the Korean Government and a National Research Foundation of Korea (NRF) grant funded by the Korean Government (MSIP) (No. 2017R1A2B4008635). The second author was supported by NRF (National Research Foundation of Korea) Grant funded by the Korean Government (NRF-2016-Fostering Core Leaders of the Future Basic Science Program/Global Ph.D. Fellowship Program).

REFERENCES

Agaba, H., Baguma Orikiriza, L. J., Esegu, O., Francis, J., Obua, J., Kabasa, J. D., and Hüttermann, A. (2010). "Effects of hydrogel amendment to different soils on plant available water and survival of trees under drought conditions." *Clean–Soil, Air, Water*, 38(4), 328-335.

Al-Darby, A. (1996). "The hydraulic properties of a sandy soil treated with gel-forming soil conditioner." *Soil technology*, 9(1), 15-28.

Bhardwaj, A., Shainberg, I., Goldstein, D., Warrington, D., and J Levy, G. (2007). "Water retention and hydraulic conductivity of cross-linked polyacrylamides in sandy soils." *Soil Science Society of America Journal*, 71(2), 406-412.

Bouazza, A., Gates, W., and Ranjith, P. (2009). "Hydraulic conductivity of biopolymer-treated silty sand." *Géotechnique*, 59(1), 71-72.

Butijn, J., and Wesseling, J. (1959). "Determination of the capillary conductivity of soils at low moisture tensions." Institute for Land and Water Management Research.

Chang, I., and Cho, G.-C. (2012). "Strengthening of Korean residual soil with β-1, 3/1, 6-glucan biopolymer." *Construction and Building Materials*, 30, 30-35.

Chang, I., Im, J., and Cho, G.-C. (2016). "Geotechnical engineering behaviors of gellan gum biopolymer treated sand." *Canadian Geotechnical Journal*, 53(10), 1658-1670.

Chang, I., Im, J., Prasidhi, A. K., and Cho, G.-C. (2015b). "Effects of Xanthan gum biopolymer on soil strengthening." *Construction and Building Materials*, 74, 65-72.

Chang, I., Prasidhi, A. K., Im, J., Shin, H.-D., and Cho, G.-C. (2015a). "Soil treatment using microbial biopolymers for anti-desertification purposes." *Geoderma*, 253, 39-47.

Chen, R., Lee, I., and Zhang, L. (2014). "Biopolymer stabilization of mine tailings for dust control." *Journal of Geotechnical and Geoenvironmental Engineering*, 141(2), 04014100.

Chenu, C. (1993). "Clay-or sand-polysaccharide associations as models for the interface between micro-organisms and soil: water related properties and microstructure." *Geoderma*, 56(1-4), 143-156.

Czarnes, S., Hallett, P., Bengough, A., and Young, I. (2000). "Root- and microbial- derived mucilages affect soil structure and water transport." *European Journal of Soil Science*, 51(3), 435-443.

Fan, T., Stewart, B., Payne, W. A., Yong, W., Luo, J., and Gao, Y. (2005). "Long-term fertilizer and water availability effects on cereal yield and soil chemical properties in northwest China." *Soil Science Society of America Journal*, 69(3), 842-855.

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

Jansson, P.-e., Kenne, L., and Lindberg, B. (1975). "Structure of the extracellular polysaccharide from Xanthomonas campestris." *Carbohydrate Research*, 45(1), 275-282.

Kim, Y.-S., Ko, H.-W., Kim, J.-H., and Lee, J.-G. (2012). "Dynamic Deformation Characteristics of Joomunjin Standard Sand Using Cyclic Triaxial Test." *Journal of the Korean Geotechnical Society*, 28(12), 53-64.

Lu, N., and Likos, W. (2004). "Rate of capillary rise in soil." *Journal of geotechnical and Geoenvironmental engineering*, 130(6), 646-650.

Osacky, M., Geramian, M., Ivey, D. G., Liu, Q., and Etsell, T. H. (2015). "Influence of Nonswelling Clay Minerals (Illite, Kaolinite, and Chlorite) on Nonaqueous Solvent Extraction of Bitumen." *Energy & Fuels*, 29(7), 4150-4159.

Silberbush, M., Adar, E., and De Malach, Y. (1993). "Use of an hydrophilic polymer to improve water storage and availability to crops grown in sand dunes I. Corn irrigated by trickling." *Agricultural water management*, 23(4), 303-313.

Smitha, S., and Sachan, A. (2016). "Use of agar biopolymer to improve the shear strength behavior of sabarmati sand." *International Journal of Geotechnical Engineering*, 10(4), 387-400.
Viero, P. W., and Little, K. M. (2006). "A comparison of different planting methods, including hydrogels, and their effect on eucalypt survival and initial growth in South Africa: scientific paper." *Southern African Forestry Journal*, 2006(208), 5-13.
Yang, H., Rahardjo, H., Leong, E.-C., and Fredlund, D. G. (2004). "Factors affecting drying and wetting soil-water characteristic curves of sandy soils." *Canadian Geotechnical Journal*, 41(5), 908-920.
Yang, J., Song, K., Kim, B., Hong, S., Cho, D., and Chang, Y. (2007). "Arsenic removal by iron and manganese coated sand." *Water Science and Technology*, 56(7), 161-169.