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Soil water retention and vegetation survivability improvement using microbial biopolymers in drylands

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Abstract. Vegetation cover plays a vital role in stabilizing the soil structure, thereby contributing to surface erosion control. Surface vegetation acts as a shelterbelt that controls the flow velocity and reduces the kinetic energy of the water near the soil surface, whereas vegetation roots reinforce the soil via the formation of root-particle interactions that reduce particle detachment. In this study, two vegetation-testing trials were conducted. The first trial was held on cool-season turfgrasses seeded in a biopolymer-treated site soil in an open greenhouse. At the end of the test, the most suitable grass type was suggested for the second vegetation test, which was conducted in an environmental control chamber. In the second test, biopolymers, namely, starch and xanthan gum hydrogels (pure starch, pure xanthan gum, and xanthan gum-starch mixtures), were tested as soil conditioners for improving the water-holding capacity and vegetation growth in sandy soils. The results support the possibility that biopolymer treatments may enhance the survival rate of vegetation under severe drought environments, which could be applicable for soil stabilization in arid and semiarid regions.

Keywords: vegetation; xanthan gum starch; water retention; drought tolerant

1. Introduction

Vegetation cover plays a number of roles in controlling soil erosion, such as mitigating surface runoff and severe soil losses in most climate zones (Chang *et al.* 2015a). The stability of a slope, which is often comprised of well-drained and low-cohesive soil, depends on the mechanical reinforcement provided by the plant roots in the soils and on the soil-water suction characteristics (Roering *et al.* 2003, Chirico *et al.* 2013). Vegetation dynamics is one of the key indicators of an ecosystem's response to climate change. Climate change alters numerous site factors and the biochemical processes of vegetation communities, which affect nutrient and water availability and, in turn, affect the root distribution (Hufnagel and Garamvölgyi 2014). Therefore, soil erosion control will likely continue to present problems.

Global average temperatures have increased over the past 100 years due to the increase of greenhouse gases. The global warming phenomenon becomes more severe in arid and semi-arid regions (Huang *et al.* 2012, Ji *et al.* 2014). Arid and semi-arid areas are classified due to low, erratic rainfall, long periodic droughts, and high evaporation levels (Maghchiche *et al.* 2010). Generally, soils in these areas easily erode because they contain a low amount of organic acids and natural substances that can provide shear resistance against erosion (Marinari *et al.* 2000). Furthermore, a temperature increase reduces the water storage capacity of the soil and may exceed the drought tolerance of vegetation, which is known to be a limiting factor for seedling survival (Cao 2008, Chang *et al.* 2015a).

Thus, to reduce the effect of increasing temperatures on the survival of seedling in drylands, the use of gel conditioners for irrigation water retention becomes an important issue in which hydrophilic hydrogels are expected to maximize the efficiency of vegetation water uptake (Koupai *et al.* 2008).

In general, cross-linked polymers, such as polyacrylamide (PAM) (Silberbush *et al.* 1993), absorbent polymers (El-Asmar *et al.* 2017), and biopolymers (Chang *et al.* 2016b, c, 2017) are common hydrogels used to improve the water storage of soils. Although absorbent polymers at 0.1%-0.2% of the soil mass are recommended, El-Asmar *et al.* (2017) suggested a minimum effective supplementation of 0.4% to improve water savings within a sandy clay loam. Meanwhile, Chang *et al.* (2015a) showed that a 0.5% biopolymer mix demonstrates the potential to significantly reduce soil erodibility while improving soil water retention and vegetation germination for residual soils and sand.

Due to environmental concerns in recent years, the search for and the development of sustainable technologies has been pursued. As biopolymers have a high water holding capacity, soil-bonding improvements involving them have received more attention from geotechnical

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engineering researchers. A considerable amount of literature has been published on the applicability of biopolymers for soil strengthening (Chang and Cho 2014, Chang *et al.* 2016a, Lee *et al.* 2017, Qureshi *et al.* 2017, Chang and Cho 2018), hydraulic conductivity reducing (Chang *et al.* 2016b), dynamic property improvement (Im *et al.* 2017), and water treatment (Kwon *et al.* 2017).

In this study, to evaluate the effect of biopolymers on vegetation growth, two testing trials were conducted for different purposes.

The first test was performed during the autumn season (September 12-26) in Korea. Therefore, popular cool-seasoned turf grasses (perennial ryegrass, Kentucky bluegrass, and tall fescue) were chosen. The seeds were cultured in a greenhouse with an in-situ soil that was treated with 0.5% xanthan gum: a starch that had a conditioning ratio of 3:7. The test aimed to investigate the most appropriate grass type for the second vegetation test program.

The second trial aimed to evaluate the effect of the various biopolymer types on vegetation growth of perennial ryegrass under a severe drought condition simulated in an environmental control chamber. Jumunjin sand was used in the second test and was treated with xanthan gum and starch biopolymers in which both biopolymers mixed in the soil with 0.5% biopolymer-to-soil content. Furthermore, the unconfined compressive strength (UCS) was measured to investigate the strength and stiffness of the soils. At the end of the study, the effects of the biopolymers on both seed germination and vegetation growth were obtained. Furthermore, the best biopolymer, which shows a positive effect on reducing water stress for seedlings, is suggested.

2. Materials and methods

2.1 Materials

Soil

In-situ soil (Seosan, Korea) and jumunjin sand, which is a standard sand material in Korea, were used in this study. Both soils are classified as poorly graded sand (*SP*). The particle size distribution curves of the soils are presented in Fig.1. The basic soil properties are summarized in Table 1.

The use of sands in the vegetation tests can reflect the worst condition of the soils and help us more clearly observe the effect of the biopolymers. The sands are treated with a 0.5% biopolymer-to-soil ratio based on mass (m_b/m_s).

Biopolymer: Xanthan gum

Xanthan gum (XG) is composed of pentasaccharide-repeating units comprised of glucose, mannose, glucuronic acid, and two types of carboxyl groups: acetate and pyruvate (Jansson *et al.* 1975). XG has been used in the oil drilling industry to thicken drilling fluids and improves the drilling effectiveness. XG also has the best performance in decreasing the hydraulic conductivity of soils (Bouazza *et al.* 2009) and in strengthening soils (Chang *et al.* 2015b, Chang *et al.* 2018a). Research grade XG (Sigma Aldrich; CAS No.11138-66-2) was used in this study.

Biopolymer: Starch

Starch (ST) is composed of some monosaccharides or sugar molecules linked together with α-D-(1-4) and/or α-D-(1-6) linkages (Tester *et al.* 2004). In the paper industry, starches are used to “size” the paper sheets through the chemical interaction between the cationic charges of ST and the negatively charged paper fibers (Lindström *et al.* 2005). Furthermore, modified ST demonstrates excellent performance in geotechnical engineering applications, such as improving the shear strength, compressive strength, and the permeability of soils (Khatami and O’Kelly 2012, Ayeldeen *et al.* 2016). Research grade ST (Sigma Aldrich; CAS No. 9005-25-8) was used in this study.

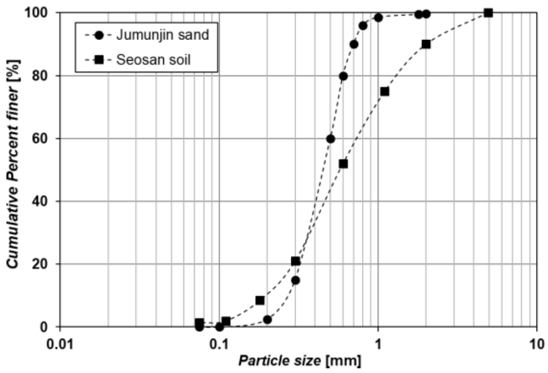

Fig. 1 Particle size distribution of the studied soils

Table 1 Properties of soils

Properties	Jumujin sand	Seosan soil
Unified soil classification system	SP	SP
Specific gravity, G_s	2.65	2.66
Mean particle size, D_{50}	0.45	0.58
Coefficient of uniformity, C_u	1.39	3.94
Coefficient of curvature, C_c	0.76	0.96

Biopolymer: Xanthan gum-Starch mixture

Unmodified ST is known to be unstable due to its degradation or dissolution (Cheng and Wintersdorff 1981). Therefore, in food technology, a small amount of XG is often added to a ST gel to provide an increase in gel viscosity that is proportional to the gum concentration (Sikora *et al.* 2008). XG works as a protective colloid, improving the ST resistance to elevated temperatures and acidic moieties (Sikora *et al.* 2003). The addition of XG to a ST gel plays a significant role in the retardation of ST gel hardening and improving water retention due to the relatively larger molecule structure of XG, which can immobilize more water molecules. To investigate the effect of XG-ST mixtures on vegetation, XG and ST were mixed in 3:7 (3XG-7ST) and 7:3 (7XG-3ST) ratios by mass.

Vegetation

Perennial ryegrass *(Lolium perenne L.)*, Kentucky bluegrass (*Poa pratensis L.)* and tall fescue (*Festuca arundinacea L.*) are common cool-season turfgrasses that have been utilized to improve the environment for humans for more than 30 centuries. Moreover, the turfgrasses used in this study are known to have functional benefits, such as soil erosion control, flood control, and dust stabilization (Beard and Green 1994).

2.2 Experimental programs

Soil-water retention test

Biopolymer hydrogel solutions were prepared by dissolving the biopolymer in deionized water at 24°C, to achieve the target biopolymer concentration of 0.5% of the soil mass. The initial water content for soil-hydrogel solution mixing was set at 30% of the dry weight of soil.

The drying soil-water characteristics of biopolymer treated soil were obtained via a five-bar pressure plate extractor (maximum pressure capacity = 5 bar; Fig. 2). The biopolymer–soil mixtures were evenly compacted into a steel ring with a diameter of 50 mm and a height of 15 mm, providing a dry density of 1.58 ± 0.02 g/cm^3, before being saturated for 24 h. Pneumatic air pressure (u_a) was applied in steps whereby each pressure was constantly applied for 24 h.

The volumetric water content of the soil is calculated via θ_w-(ρ_d/ρ_w)·w, where w is the gravimetric water content, ρ_d is the dry density of the soil, and ρ_w is the density of the water (1.0 g/cm^3). The matric suction can be assumed by taking the u_a value.

Unconfined compression test

Cubic samples (3.5 cm × 3.5 cm × 3.5 cm) of the biopolymer treated sands were prepared to a dry density of 1.58 ± 0.02 g/cm^3. Unconfined uniaxial compressive testing was performed with a Humboldt digital master loader (HM-5030.3F). The axial strain rate was controlled at a rate of 1% strain/min according to ASTM D2166 (ASTM 2016). The test was conducted on specimens dried at 30°C in an oven. The maximum unconfined compressive strength was obtained by averaging three different measurements for each single soil condition.

Vegetation growth in an open greenhouse

The soil specimens were distributed in a vegetation tray that consisted of 12 circular sections. Each section had dimension as 60-mm in diameter and 30-mm in height. The specimens were cultured in the greenhouse with a daily water supply of 25 mL/day/specimen. The test was conducted during September for 16 days. The daily temperature variations in the environmentally uncontrolled greenhouse are summarized in Fig. 3.

Vegetation growth in the environmental control chamber

Specimens were cultured in an environmental control chamber at a temperature of 25°C, a humidity of 85%, and daylight of 12 hours/day (Table 2). During the first 30 days, a daily precipitation of 7 mL/day/specimen was supplied for seed germination and sprout growth, while a drought condition with a daily water supply of 0 mL/day/specimen was simulated after 30 days. During the drought condition, the temperature was increased to 33°C while the chamber humidity was decreased to 57% (Table 2).

The germination rate is used to estimate the viability of a population of seeds. The equation to calculate the cumulative germination rate is given as follows

(number of germinated seeds/ total seeds) × 100

When the turf grasses are subjected to water stress, they merely run out of the available water and wilt. As the green grasses were turning yellow, they were named wilted sprouts in this study. The wilting rate is calculated as follows

(number of wilted grasses/total grasses) × 100

The height of the grass is the height above the surface (Chen *et al.* 2013) (i.e., the length from the top of the main tiller to the crown). The root length was the length from the crown to the end of the main root. The means and standard deviations were calculated.

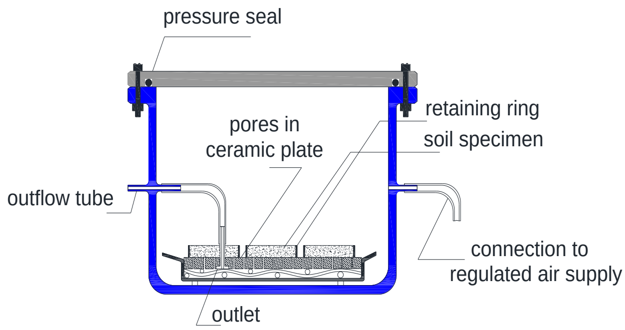

Fig. 2 Five-bar pressure plate extractor

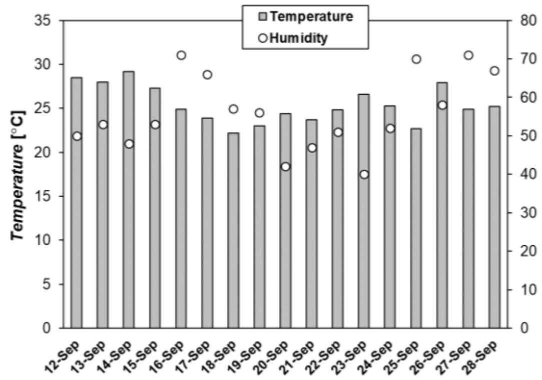

Fig. 3 Daily weather conditions in an open greenhouse

Table 2 Experimental conditions

Temperature [°C]	Humidity [%]	CO_2 [ppm]	Lighting [h/day]	Watering [mL/day]
Normal: 25	80	915	12	7
Drought: 33	57			0

3. Effects of biopolymers on the vegetation growth and soil structure

3.1 Biological effect of biopolymers on the metabolism of vegetation

Fig. 4 illustrates the effects of XG and ST on the metabolism of the vegetation (Jansson *et al.* 1975, Meléndez-Hevia *et al.* 1996, Oexle *et al.* 1999, Berg *et al.* 2002, Tester *et al.* 2004, Valpuesta and Botella 2004, Gallie 2013, Yuan *et al.* 2014, Scialdone and Howard 2015). Glucose, a universal nutrient preferred by most organisms, not only fuels metabolism but also functions as a hormone-like signaling molecule during plant growth and development (Yuan *et al.* 2014). Glucose is produced by plants through photosynthesis using light energy from the

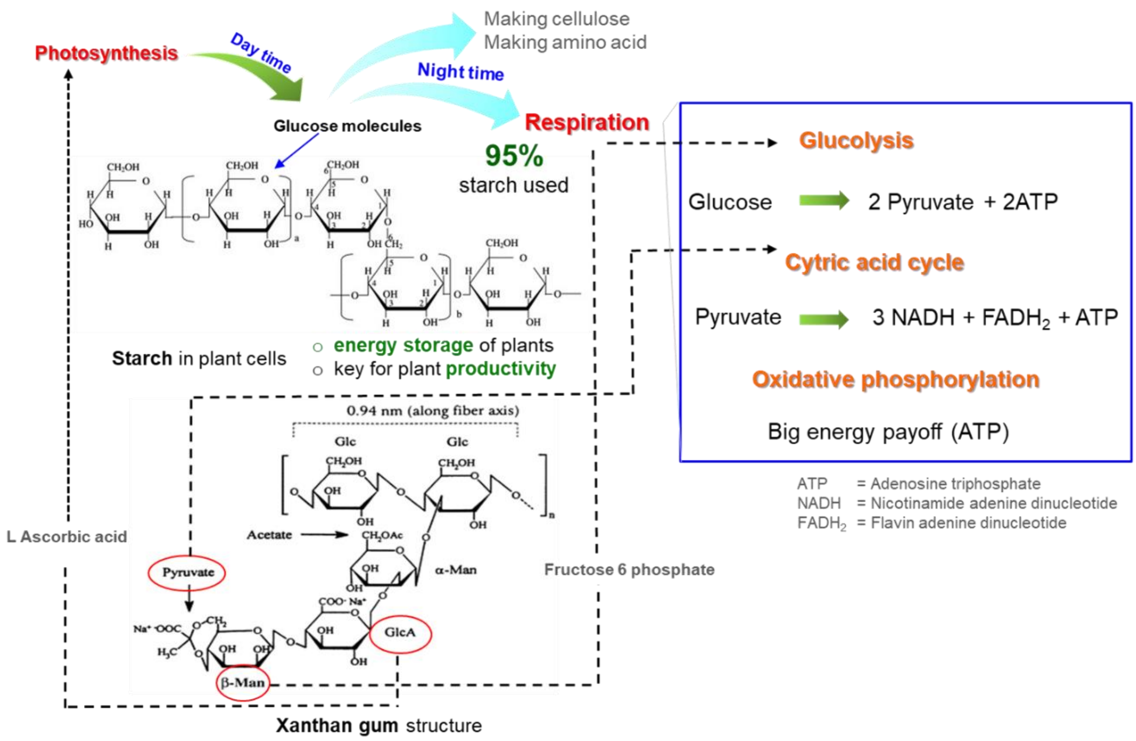

Fig. 4 Diagram of biopolymers' effect on the metabolism of vegetation (after Jansson *et al.* 1975, Meléndez-Hevia *et al.* 1996, Oexle *et al.* 1999, Berg *et al.* 2002, Tester *et al.* 2004, Valpuesta and Botella 2004, Gallie 2013, Yuan *et al.* 2014, Scialdone and Howard 2015)

sun. The plant joins glucose molecules together via glycosidic bonds to form ST. In other words, ST is an energy storage material for plants, which is why ST biopolymers are comprised of glucose molecules. When plants need glucose for respiration in the nighttime darkness, they can take glucose from the ST; 95% of all the ST is utilized by the next morning (Scialdone and Howard 2015). Thus, ST utilization is critical for plant productivity. The components of XG-mannose, glucuronic acid, and pyruvate-play different roles in photosynthesis and the respiration processes of plants. Cellular respiration happens through three major pathways, namely, glycolysis, the citric acid cycle, and oxidative phosphorylation (Oexle *et al.* 1999). The mannose group can contribute to producing pyruvate and ATP (i.e., energy) for glycolysis (Berg *et al.* 2002) The pyruvate group in XG can join the citric acid cycle pathway to produce energy (Meléndez-Hevia *et al.* 1996), whereas glucuronic acid produces the L. ascorbic acid (Valpuesta and Botella 2004) that is used in the photosynthesis process (Gallie 2013).

In general, XG and ST biopolymers used in this study contain chemical components that are required in the metabolism of plants. By mixing these biopolymers with a soil, these components can be used in seed germination and sprout growth via nutrients and/or the water uptake mechanisms of a seed and the vegetation.

3.2 The effect of biopolymers on a sand structure concerning vegetation growth

The soil structure regulates the pore size, the number of pores, the distribution of the pores, and the total porosity of the soil (Pagliai and Vignozzi 2002). Thus, the retention and movement of soil water including infiltration, permeability, percolation, drainage, and leaching depend on the soil structure. The soil structure affects plant growth by influencing the root distribution and its ability to take up water and nutrients (Pardo *et al.* 2000, Bronick and Lal 2005). The presence of biopolymers within the soil can significantly change the soil structure.

Water retention

As aforementioned, cohesionless sand is regarded to have a negligible water-holding capacity and interparticle binding ability. However, the presence of biopolymers can provide a water-holding capacity to sand that depends on the biopolymer rheology (Chang *et al.* 2016b, Chang and Cho 2018).

Fig. 5 shows the water retention curve of the 0.5% biopolymer treated sands in which the pure XG treatment shows the highest amount of water retained due to the strong hydrogen bonding between the XG and the water molecules (Young *et al.* 1994). Meanwhile, the water held by surface tension within the untreated sand is easy to break under high suction. Compared to XG-treated sand, the ST-treated sand has a lower water-retention capability, which may imply weaker bonding between the ST and the water. The viscosities of XG solutions are generally 2 to 3 times higher than those of ST solutions at same solution concentration (Abson *et al.* 2014). Thus, the water-retention efficiency via biopolymer treatment may increase in the order of XG-treated > XG-ST mixture-treated > ST-treated > untreated conditions.

The amount of water within the soil plays an important role in seed germination and vegetation growth (Tu and Tan

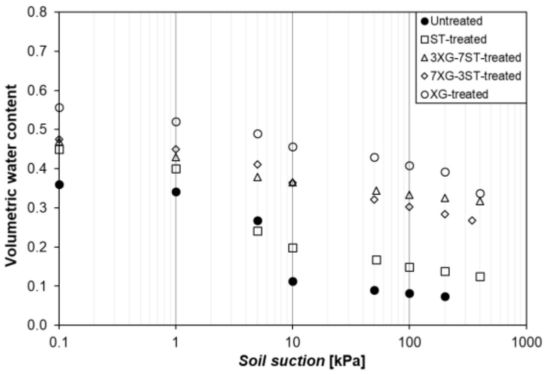

Fig. 5 Water retention of 0.5% biopolymer treated sands

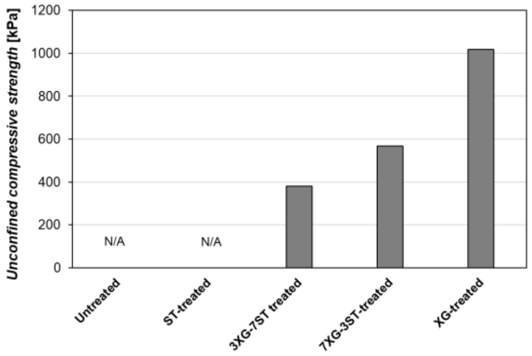

Fig. 6 Unconfined compressive strength of m_b/m_s = 0.5% biopolymer treated sands

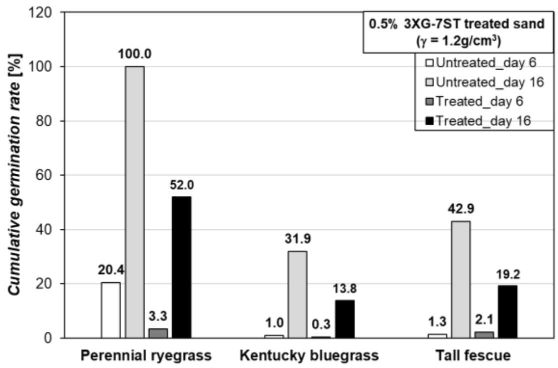

Fig. 7 Germination of turfgrasses in m_b/m_s = 0.5% 3XG-7ST-treated sands

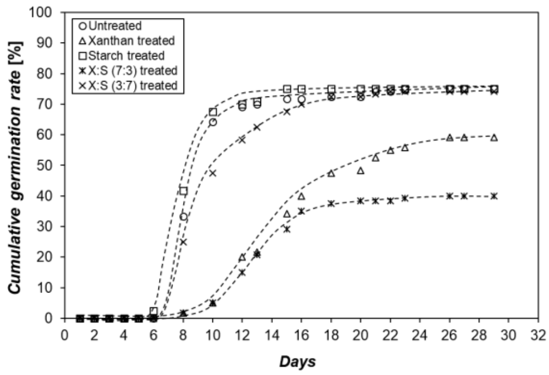

Fig. 8 Seed germination rate on m_b/m_s = 0.5% biopolymer-treated sands

2003). Soil with a sufficient amount of water can provide proper aeration within the soil. However, waterlogging can occur due to excessive water in the soil, which causes insufficient oxygen in the soil pores. As a result, seed germination is restricted due to both poor aeration and inadequate water supply (Dasberg and Mendel 1971).

3.3 Unconfined compressive strength

The high viscosity of biopolymers can improve the inter-cohesion between the sand particles, which in turn significantly increases the compressive strength of the sand. Fig. 6 shows the compressive strength values of sand treated with different biopolymer types. UCS data from the untreated sand and ST-treated sand could not be obtained due to the particles being unbound as they were dried. Among the biopolymers used in this study, the higher the XG ratio within the soil, the higher is the compressive strength obtained. XG demonstrates the best performance in strength improvement for sand due to its high viscosity that strongly binds the sand particles. The strength data reflect the softness of the soil for the germination of seeds or for root penetration (e.g., root size and length) into the soil. Furthermore, the decrease of the dry density was due to the pore-filling effect of biopolymers.

In general, biopolymers affect the soil structure and in turn change the aeration, water uptake condition of the soil environment, and root-soil contact. Thereby, biopolymer concentrations and types influence the growth mechanism of vegetation. Their effects are described in the next section.

4. Germination capacity of turf grasses

Fig. 7 shows the germination rate of the varying turfgrasses used in this study, monitored for 6 days and 16 days. With respect to the Seosan soil, Kentucky bluegrass shows the slowest germination behavior, while tall fescue becomes moderate, and perennial ryegrass shows the quickest germination performance. Also, this trend could be seen for the treated soils. It is observed that biopolymers, even though they can hold more water for soil, they did not form a good environment for seeds to germinate. At day 16, the germination rates for the treated soil were approximately half of those for the natural soil. An answer to this phenomenon can be found in the next section.

5. Effects of biopolymers on the growth and survivability of perennial ryegrass

5.1 Effects of biopolymers on seed germination

The cumulative germination rate is shown in Fig. 8. Untreated sand, ST-treated sand, and a 3XG-7ST mixture showed the best germination rates. This was because good aeration conditions were formed within the soils. The pores contained a proper ratio of air and water for seed germination. As the amount of XG increased, a significant change in the amount of water within the soil may lead to unbalanced air-water circulation or waterlogging, which in

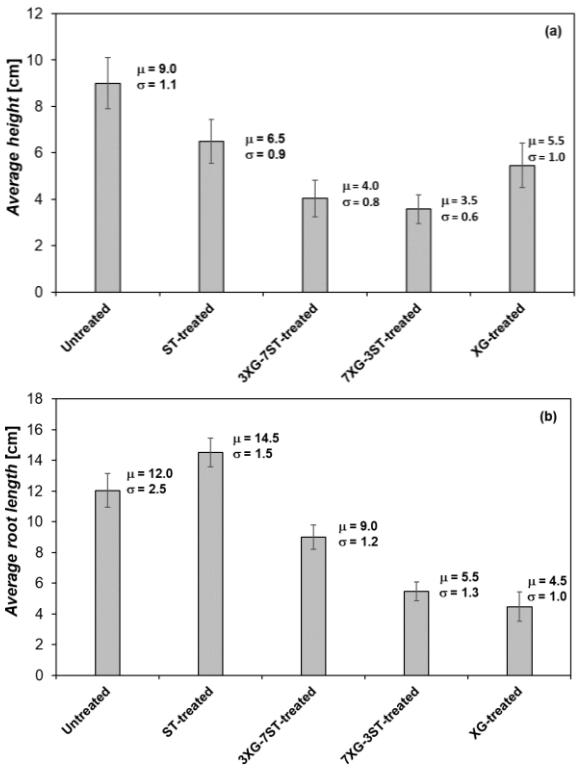

Fig. 9 Vegetation height (a) and root growth (b) in m_b/m_s = 0.5% biopolymer-treated soils

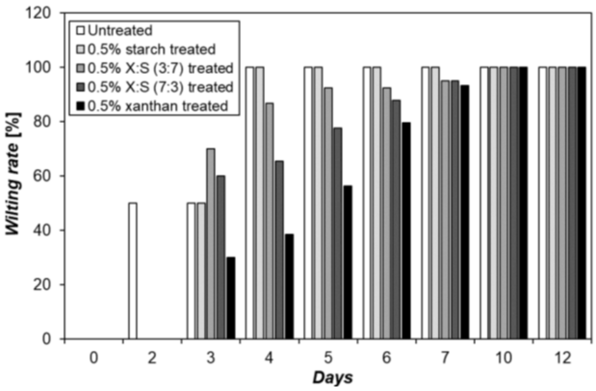

Fig. 10 Effect of biopolymers on the survivability of ryegrass

turn could delay the germination of ryegrass seeds. Furthermore, a thin, hard soil surface was formed on the soil specimens treated with a high XG concentration, which caused difficulty for the sprouts to penetrate the soil.

The germination behavior also differs with soil type, where the aeration condition of the soil seems to be the primary factor, where the tallest grass height of 9 cm has been observed in the untreated sand medium (Fig. 9(a)) while the second tallest group was found in the ST-treated sand condition. The lowest grass had a height of 2.5 cm and was obtained from the 7XG-3ST-treated condition.

The effects of the biopolymers were not only on the height, but also on the root system of the ryegrass (Fig. 9(b)). The root actively developed within the untreated, and ST-treated sands due to aeration conditions and nutrients supplied by the ST biopolymer. Meanwhile, the root system in the XG-treated sand was the shortest. The responses of vegetation within the XG-ST mixture-treated sands differed with the amount of XG and ST used. The higher the ST concentration, the longer the root system. The hard surface of the soil (i.e., the high compressive strength) and water near the soil surface (i.e., high water retention) might be important factors for the root lengths observed

5.2 The effect of biopolymers on the survivability of vegetation under drought conditions

Under the drought condition, the ryegrass started wilting due to water loss. The wilting rate of the ryegrass is shown in Fig. 10. The ryegrass in the ST-treated sand wilted after three days. The lowest rate can be seen in the case of the XG-treated sand. On the 4th day, all of the grasses in the untreated and treated sand wilted. The lowest wilting rate was observed in the grasses planted in the XG-treated sand. In the same cultural condition, the wilting of grass significantly depends on the amount of available water within the soil. As mentioned in Section 3.2, the XG-treated sand has higher water retention compared to the other biopolymer-treated sands. In other words, under drought conditions, XG fostered less water loss, which can explain why the XG biopolymer demonstrated the best performance in improving the survivability of grass under drought conditions.

6. Discussion

The experimental results demonstrate that different biopolymers have different roles in the growth and survivability of ryegrass, which is due to the different water reactions of the biopolymers. The higher the amount of XG, the lower the free pore space within the soil. This is because the XG hydrogel absorbs the daily water, swells, and blocks the pore spaces. It is believed that the water-holding capacity of the biopolymer is an impacting factor when deciding what ratio of biopolymer concentration should be used to avoid waterlogging. Therefore, the authors suggest that biopolymers- due to their high swelling capacity even with concentrations as low as 0.5%- should not be used in normal conditions where water is supplied daily.

However, our results demonstrate the crucial role that biopolymers can play in the survivability of ryegrass owing to their high water holding capacity under drought stress. In this condition, more water is contained in the pore spaces of the XG-treated sand. This, in turn, makes water more available to the ryegrass. The survivability of the ryegrass planted in treated sand significantly depends on the biopolymer type. In this study, XG shows the best performance with respect to water stress reduction for sprouts. Furthermore, the XG application method has a significant effect on increasing particle binding, which in turn can control the loss of fine soil particles subjected to wind or water erosion. The authors suggest that the amount of XG used should not be higher than 0.5% to control the softness of soil.

In conclusion, biopolymers in sand from arid or semiarid regions can serve as essential tools for increasing water use efficiency and vegetation survivability and for reducing wind erosion and water erosion.

7. Site application

A site application to evaluate slope erosion resistance concerning vegetation, using biopolymer treated soils, started on September 8, 2017, in Andong City, Korea. Fig. 11 shows the procedure of biopolymer soil treatment along a cut slope with a 45° slope. After cleaning the construction site, the slope was covered with coconut erosion mats that are known to be a useful fiber material in controlling slope erosion.

Fig. 11 Biopolymer-soil application on a cut slope

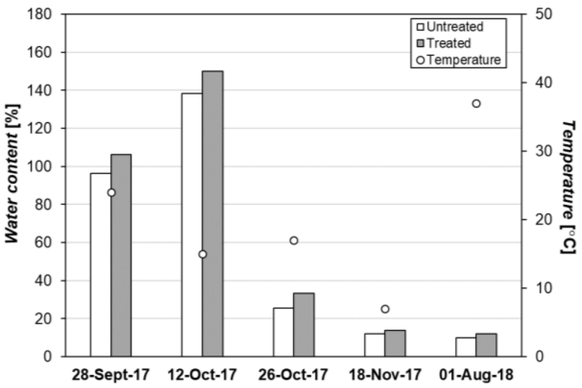

Fig. 12 Change in temperature and water content within the monitoring time

Fig. 13 Effect of biopolymer on vegetation growth

Then, a mixture of cultured soil, 0.5% XG-ST hydrogel solution and seeds was applied along the slope via the spraying method. In this study, the changes in water content and vegetation growth condition under natural condition was monitored from day 20 and ended on August 1, 2018. The changes of the water content and temperature during the monitoring are summarized in Fig. 12. The shift in temperature could affect the water retention of the soils. As the soils are subjected to the same temperature condition, the amount of water within treated soil was higher than that of untreated soil. This demonstrated that XG-ST hydrogel improved the water holding capacity of soils, which was anticipated from the laboratory soil-water retention test results. The difference in water content, even though not significant, improved the environmental condition within the treated soil, fostering faster germination and growth of the vegetation (Fig. 13).

8. Conclusions

Water storage is currently one of the most pressing issues in arid and semiarid areas. Biopolymer supplementations of sand are one of the most efficient water conservation practices. The present study demonstrates that using a xanthan gum biopolymer as a soil amendment increases the available water that is present in the sand and, in turn, increases the plant water uptake under drought conditions. Moreover, xanthan gum application methods can enhance particle binding in the sand. The effectiveness in water retention and the soil cohesion improvement due to the use of xanthan gum provide a promising future for its use as a tool to deter the effects of wind erosion for crops grown in arid or semiarid areas.

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