The 2025 World Congress on
Advances in Structural Engineering and Mechanics (ASEM25)
BEXCO, Busan, Korea, August 11-14, 2025

Preliminary Study on Integrating Biopolymer with Injection Method

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ABSTRACT

Biopolymers have a promising future in soil improvement. Studies have been conducted in order to further develop the technology. For unreachable or deep soil improvement, implementing the wet or dry mechanical mixing method poses significant challenges. Injection method, which is commonly found for grouting applications, have been reintroduced through few studies to face the challenge. By integrating the method with biopolymer, the idea of implementing biopolymer for hard-to-reach area is feasible. One additional factor, injectability, is crucial for integrating the injection method and biopolymer. Injectability is strongly influenced by internal factors (biopolymer-induced) and external factors (injection apparatus and environment). Under similar conditions, biopolymer's properties, behaviors, and responses can differ for each type. This study specifically reviewed the injectability of biopolymers with respect to its concentration and injection pressure. Post-injected soil's permeability and strength are also covered in this study as they are crucial parameters for grouting applications. Generally, higher biopolymer concentration leads to higher strength and better effect on controlling permeability. However, more concentration of biopolymer also leads to a more viscous mixture. Highly viscous biopolymer mixtures tend to need more energy to be displaced, hence requiring more injection pressure. Crosslinked biopolymer injection is discussed in this study. More experimental study is highly recommended in order to achieve fully-integrated biopolymer injection. Through this preliminary study, further development of biopolymer studies and applications by injection method can be expected.

1. INTRODUCTION

Soil improvement is a deliberate effort in order to enhance the quality of soil, which

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4) Professor

is an essential preliminary step for any ground-related purpose. Generally, soil improvement can be done through different methods, depending on the existing internal and external factors. Internal factors inherent to the soil mass itself including properties and initial conditions, whilst external factors are activities from outside the soil mass that affects the soil mass conditions as a whole.

Admixtures method is a soil improvement method involving usage of substances to enhance soil. For decades, the use of cement has been dominating the field mainly because of its versatility and durability. Despite its excellent performance, cement is considered very harmful to the environment. Referring to Fig. 1, the annual production volume of cement has been consistently produced around 4 billion metric tons or more annually for a decade and its estimated price has been growing steadily each year for up to 60%. Additionally, each ton of cement production emits around 800 to 900 kg of carbon dioxide (CO2) which summed up to a huge amount of greenhouse gas emissions. While there are proven methods to reduce CO2 emissions by 40%, such as Limestone Calcined Clay Cement (LC3), the amount of total greenhouse gas emissions is still considered high. That being said, researchers have been studying and proposing multiple eco-friendly alternatives for cement-based applications such as: microbially induced calcium carbonate precipitation (MICP), enzyme induced calcium carbonate precipitation (EICP) and biopolymer-based soil treatment (BPST).

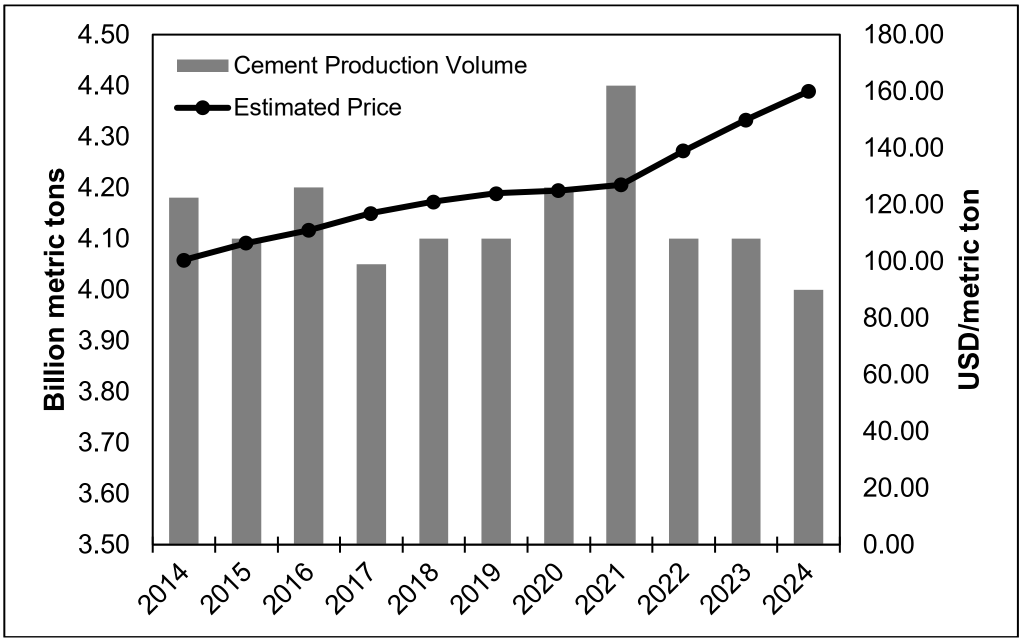


Fig. 1 Annual cement production volume and estimated price trend (US Geological Survey 2025)

Former studies have shown that BPST are a breakthrough for green and sustainable soil improvement on various applications, not to mention the cost-effectiveness of some biopolymers (Chang et al. 2016b, Yegin et al. 2017, Khattab et al. 2024). Biopolymers have diverse characteristic and quality, some of which have excellent performance. Some of the applications are non-other than enhance oil recovery or EOR (Ahearn 1969, Yegin et al. 2017, Clinckspoor et al. 2021, Khattab et al. 2024), embankment (Kwon et al. 2023), slope (Lee et al. 2023a), foundation (Ayeldeen et al. 2017), vegetation (Tran et al. 2019), liquefaction control (Park et al. 2025), erosion control (Lee et al. 2025), and so on. Efforts on improving the technology have been advancing, the reintroduction of crosslinking improves biopolymers significantly which is especially useful to enhance its mechanical strength and permeability control. However, the implementation of it is limited on shallow grounds as it is commonly utilized as hydrogel, which production involves conventional mixing technique. Hence, it is a challenge to implement biopolymers for deep or hard-to-reach region.

To reach the hard-to-reach region, the concept of injecting material is reintroduced. It shares the same principle with grouting method, which involves injecting liquid material called grout into soil voids. Conventionally, grout is cement-based material. Grouting itself can be classified based on its function, such as compaction grouting, permeation grouting, jet grouting, and so on. Conceptually, biopolymers can be implemented as permeation grout materials since they share similar properties. Hence, utilizing biopolymer as grout material is feasible, which ignited the idea of the biopolymer injection. However, deep understanding and preliminary studies need to be done in order to further investigate biopolymer injection. This study serves as the preliminary study for the topic with polysaccharide-based biopolymer as the main observation subject.

2. POLYSACCHARIDE-BASED BIOPOLYMER

Biopolymer is a macromolecule made of monomers produced by living organisms. All the way back from 1960s, biopolymers have started to be studied for enhanced oil recovery (EOR) as surfactants due to its viscosity-building performance and eco-friendliness (Ahearn 1969 and Lipton 1974). The most common biopolymer type to be utilized for geotechnical applications is carbohydrate type, specifically polysaccharide-based biopolymer (PsBP). Aside from being cost effective since it is abundant in nature, there are several factors that make PsBP as the most suitable biopolymer type for geotechnical purposes. Each unit of polysaccharides are made of repeating monosaccharides, where monosaccharide generally has multiple hydroxyl (-OH), which allow glycosidic bond to occur between them. Glycosidic bond is formed of a monosaccharide’s anomeric carbon with another molecule’s hydroxyl group. Environment -wise, most polysaccharides have obtained GRAS (Generally Recognized As Safe) status from the U.S. Food and Drug Administration (FDA), proving that they are non-toxic for human body and thus environment. Furthermore, most PsBP are biodegradable by enzyme. Enzyme can break down PsBP’s chain into simpler structure which also affects the biopolymer stability in the process (Soldi 2004).

To show the current trend inside the polysaccharide-based biopolymer group, article, review article, and proceeding paper documents within last 5 years period (2020-2024) were observed through Web of Science (Clarivate™ database 2025) with specific PsBP name and “soil stabilization” as the keywords. Soil stabilization was chosen as the search criteria as it is one of the most common BP application in geotechnical field. Out of 104 relevant results from Web of Science, as summarized in Fig. 2, the most studied PsBP for soil stabilization purpose is xanthan gum.

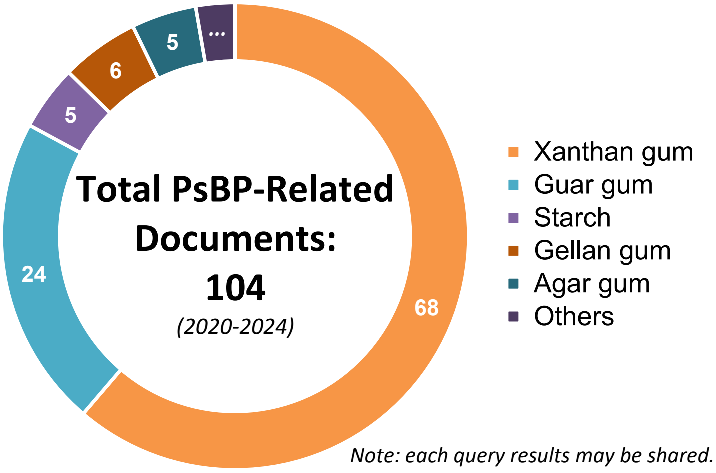
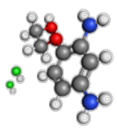
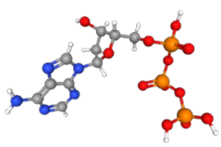
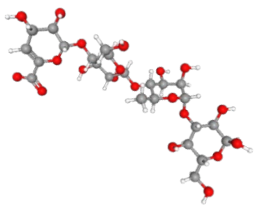
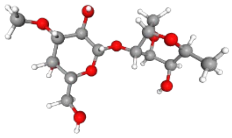
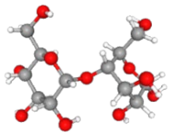


Fig. 2 Biopolymer-related documents in 2020-2024 period (Web of Science, Clarivate™ database 2025)

Following the trend results, unique characteristic and behavior of some common PsBP were summarized in Table 1. Each PsBP's unique properties make it suitable for various applications. The gelation process of biopolymer hydrogel can be influenced by either time, temperature, pH, radiation, or ion. Biopolymer's diverse gelation behavior have different advantages. Time-based gelation, the most studied gelation behavior, is easy to control and often requires no external triggers which makes it suitable for in-situ applications. Thermal-based gelation makes the biopolymer ideal for a certain range of temperature and allow rapid gelation through temperature control (Ruel-Gariépy 2004). Ion-based gelation allow a controlled gelation and may improve the BP hydrogel's stability.

Table 1. Common PsBP details and behaviors

PsBP	Source	Chemical formula	Chemical structure	Behavior
Xanthan gum	*Xanthomonas campestris* (bacterial)	C8H14CL2N2O2		- Water soluble - Time-based gelation
Guar gum	Guar bean endosperm (plant)	C10H14N5 Na2O12P3		- Cold water soluble - Time-based gelation
Gellan gum	*Sphingomonas elodea* (bacterial)	C24H37O20-		- Cold water soluble - Thermal + ion-based gelation - Partially thermoreversible in present of cations

Agar gum	Red algae (algal)	C14H24O9		- Hot water soluble - Thermal-based gelation - Thermoreversible
Starch (e.g. Potato)	*Solanum tuberosum* (plant)	C12H22O11		- Soluble in water with certain heating - Time-based gelation

For geotechnical applications, strength and hydraulic conductivity are generally considered as crucial parameters. PsBP-treated soils' strength from various former studies were observed in this study. The observed studies were limited with similarly sized grains to ensure an apple to apple comparison as seen in Fig. 3. Jumunjin sand, which is a well-known sand in South Korea with coarse to medium particle size distribution, and similarly sized reference sands has been chosen as the benchmark for PsBP-treated sand. Biopolymer-treated soils' strength are commonly observed through unconfined compressive strength (UCS) test and the numbers can vary due to their distinguishable properties, characteristics, and behaviors to the soil. Fig. 4 summarized the unconfined compressive strength reported in various studies. Concentration was stated to show that higher treatment concentration leads to higher strength. Not only concentration, curing time was also stated since PsBPs' strength generally increases with time. It is shown that PsBP-treated sands' strength is comparable to 5% usage of OPC, even though less concentration was employed. PsBP-treated sands tend to have high dry strength, but weak to submersion. Considering XG, its strength plummet significantly after immersion and the strength fully dispersed after a day due to swelling behavior of XG (Lee et al. 2023b).

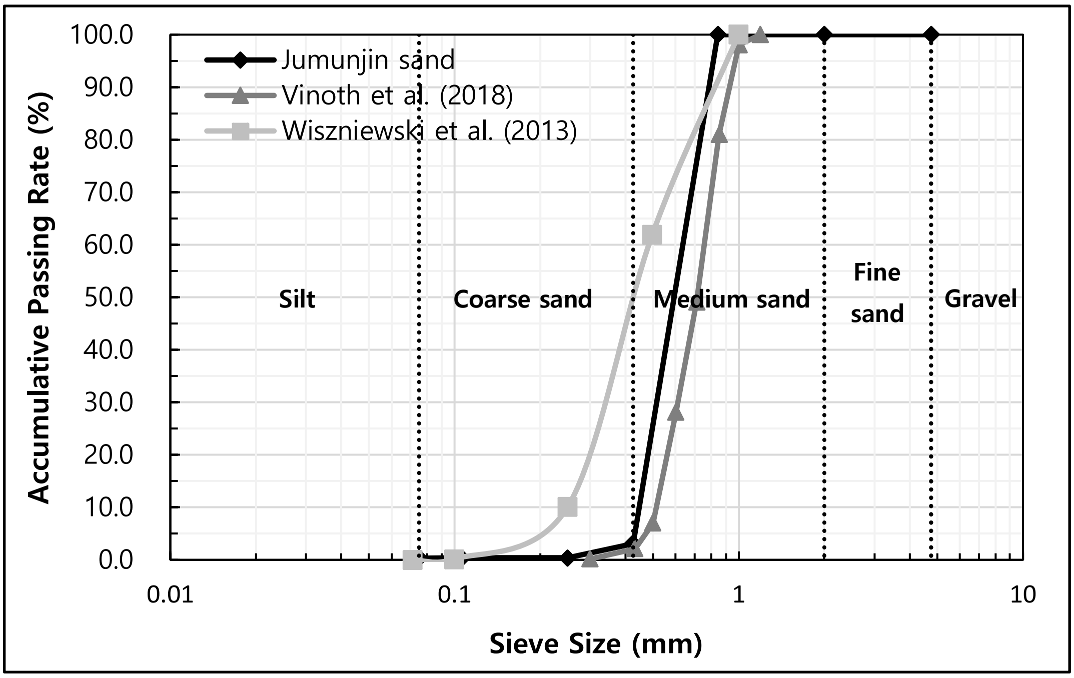


Fig. 3 Particle size distributions of coarse to medium sands, including Jumunjin sand and reference sands from Vinoth et al. (2018) and Wiszniewski et al. (2013).

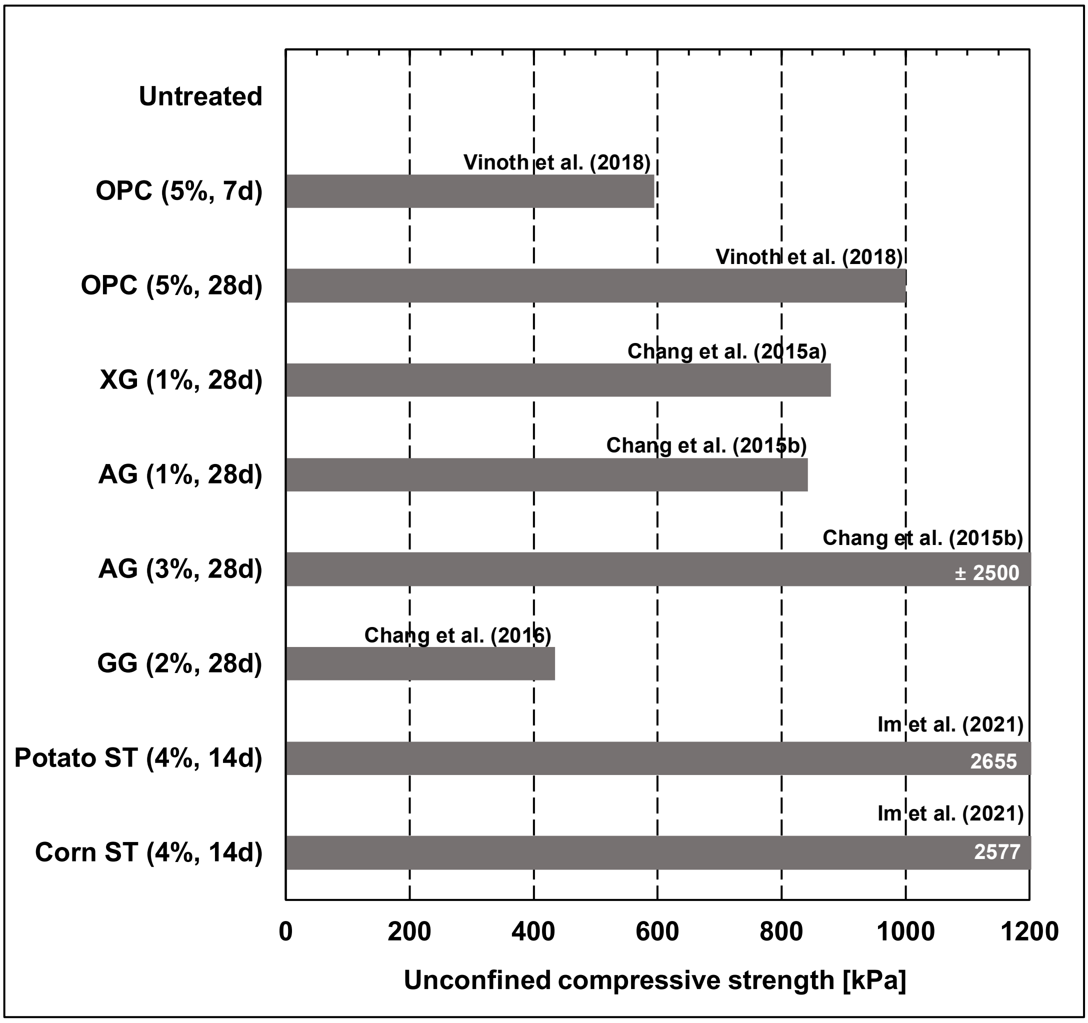


Fig. 4 Unconfined compressive strength comparison of OPC and PsBP-treated sands. Data compiled from Vinoth et al. (2018), Chang et al. (2015a), Chang et al. (2015b), Chang et al. (2016), and Im et al. (2021).

Despite PsBPs having hydrophilic behavior, they can still effectively reduce hydraulic conductivity via pore-clogging. Unlike strength parameter which can depend on time, it is considered not significant in terms of hydraulic conductivity since only slight increase can be noticed with longer curing time (Wiszniewski et al. 2013). To further explain hydraulic conductivity and its relationship with biopolymer concentration, Fig. 5 is presented after related former studies with XG as its biopolymer subject (Wiszniewski et al. 2013 and Lee et al. 2021). Hydraulic conductivity is effectively reduced as higher biopolymer to water concentration is applied.

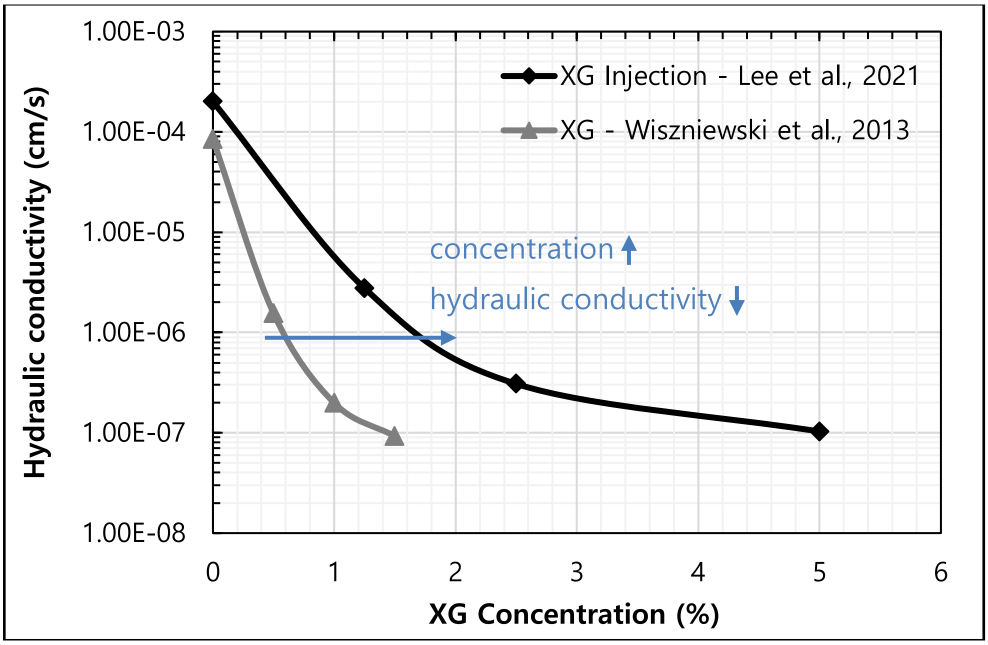


Fig. 5 Relationship between hydraulic conductivity and concentration of XG-treated sand (Lee et al. 2021 and Wiszniewski et al. 2013)

3. BIOPOLYMER INJECTABILITY

Injectability is a parameter to determine a material's ability to flow due to pressure or force. Biopolymer's injectability is determined by some aspects, such as rheological properties, injection pressure, aperture size, gelation time, and chemistry formulation stability. Some of the keys of biopolymer rheological property, including viscosity and shear behavior, were studied in this study, together with its connection with injection pressure.

Most biopolymers are utilized as hydrogels; hence they have pseudoplastic behavior and are classified as non-Newtonian fluid. Non-Newtonian fluid generally uses effective viscosity for measurement since it changes with shear. While the biopolymer's pseudoplastic behavior varies with its viscosity, the shear thinning behavior applies to each of them despite being differently viscous. Shear thinning behavior infers to the decreasing viscosity on increasing shear rate. The Ostwald–de Waele relationship is a power law with a principle where a relative change in one parameter affects in a relative change on another parameter. Relevant studies (Clinckspoor et al. 2021; Feng et al. 2023) applied the Ostwald–de Waele relationship, shown in Eq. 1, to observe complex rheological behavior. There being said, fluid viscosity (μ) accounts flow consistency index (K), shear rate ($\dot{\gamma}$), and flow behavior index (n). Power law index of Newtonian fluid is 1, while for non-Newtonian fluid it can be classified into pseudoplastic with value under 1 or thickening fluid with value above 1.

$$\mu = K \cdot \dot{\gamma}^{n-1} \tag{1}$$

Generally, biopolymer hydrogel's viscosity increase as higher biopolymer concentration is applied. Xuewu et al. (1996) studied XG hydrogel's viscosity relationship with concentration and temperature, where some data is represented in Fig. 6. XG is known to be a thermally stable biopolymer so normal temperature change doesn't have significant effect on viscosity. However, it was proven that in extreme temperature change, hydrogel viscosity can be affected significantly. Other biopolymer hydrogels may have different response towards concentration and temperature, especially thermal-based gelation biopolymers.

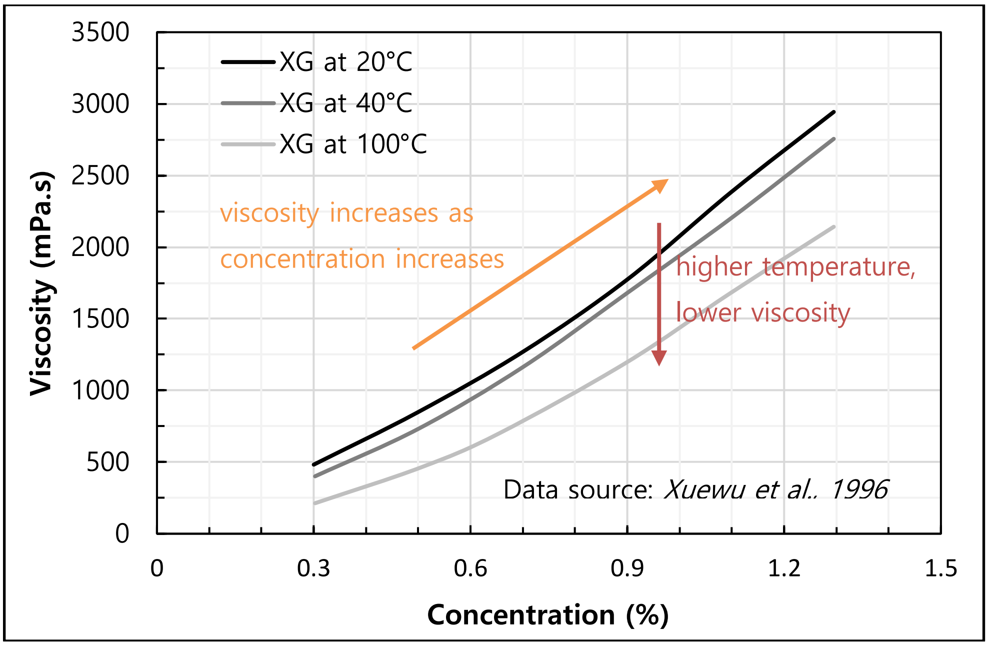


Fig. 6 Xanthan gum viscosity at varying concentration and temperature (Xuewu et al. 1996)

Since 2020, biopolymer-based permeation grouting and some related studies have surfaced and showed agreement about viscosity and injectability (Lee et al. 2021, Ryou and Jung 2023, and Falihah et al. 2025). Highly viscous solution, such as biopolymer hydrogel, tend to need more energy to be displaced since it has an increased flow resistance. Higher flow resistance leads to requiring more injection pressure to induce a flow and reduces penetration lengths. Moreover, uniformity is hard to be achieved with higher viscosity since capillary fingering may not occur. Effective viscosity of BP approaches to a relatively constant value at higher pressure gradient reflecting biopolymer's shear thinning behaviour. Viscosity relationship with shear rate explains the flow behaviour, but not the injectability. For biopolymer injection, the rate which influences injectability is not shear rate, but flow rate. Shear rate are mathematically related with flow rate, which constitutively related with injection pressure. By understanding the relationship of injection pressure and concentration, injectability of biopolymer can be controlled. A study shown the relationship between effective viscosity change and flow rate with varying injection pressure as presented in Fig. 7 (Lee et al. 2021). Effective viscosity of XG was also reported to be reduced to approximately 5% of static viscosity with injection pressures above 400kPa.

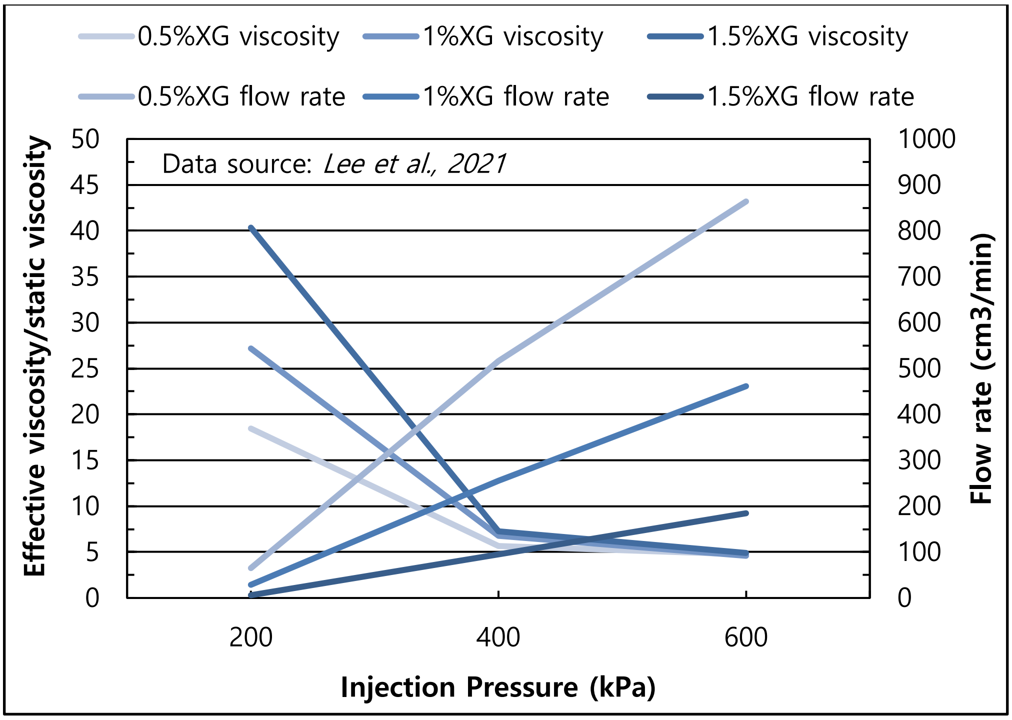


Fig. 7 XG effective viscosity and flow rate with various injection pressure. (Lee et al. 2021)

4. DISCUSSIONS

Based on the reviews, controlling biopolymer hydrogel's viscosity optimization and injection pressure are the key for biopolymer integration with injection method. By understanding the relationship between parameters, including ones that are not mentioned in the study, further optimization can be made.

Depending on the geotechnical purpose, biopolymer injection can flexibly be adjusted. The aforementioned disadvantage about PsBP hydrophilic behavior can be prevented with crosslinking that has been widely studied in vast field of study. Crosslinking a biopolymer for injection can improve the quality of the target soil; even though it is more complex, it is actually promising and feasible. Comparing to other types of crosslinking, ion crosslinking serves as the most compatible crosslinking method through injection as crosslinker can be applied as liquid solution. In order to inject crosslinked biopolymer, additional details need to be considered. Several connecting considerations include crosslinked biopolymer to water mix ratio, biopolymer injection pressure or flow rate, and crosslinking method. These 3 considerations have a direct impact on injecting the crosslinked biopolymer.

It is commonly known that higher concentration of biopolymer leads to higher strength; however, in crosslinking, the additional crosslinker concentration must be carefully estimated since optimized biopolymer to crosslinker mix ratio may vary. In the case of chromium-crosslinked xanthan gum, very high chromium concentration to water may lead to fissures development inside the hydrogel due to over-crosslinked.

If crosslinking is controlled correctly, the application of crosslinked biopolymer can be implemented for waterflow-related problems or even advanced geotechnical problems.

Learning and understanding a biopolymer's behavior and response to their crosslinker can be very useful, especially to determine crosslinker to use for certain condition. As example, calcium-crosslinked xanthan gum can rapidly harden which makes it beneficial to use for cases that requires immediate strength, such as a pipe burst case. Simple submersion test was done on calcium-crosslinked xanthan gum as part of the preliminary study and observed for 10 days. From qualitative observation, calcium-crosslinked xanthan gum gets eroded each day, but can maintain its initial strength well during the period with slight decrease.

Biopolymer's viscosity increases with the occurrence of crosslinking, hence requiring higher shear rate to flow the biopolymer hydrogel (Stojkov et al. 2021). Higher shear rate is proportional to higher pressure which can be troubling for implementation, not to mention that some crosslinker react very rapidly with the biopolymer. Through this study, a multi-channel injection is highly recommended. Moreover, this method allows crosslinking to be postponed until contact, hence, reducing the minimum injection pressure needed for a crosslinked biopolymer. By injecting the biopolymer and crosslinker solution through different channel, even rapid crosslinking is allowed to occur for a certain time which can be calculated with an equation. However, further study regarding its homogeneity, penetrability, and relevant parameter should be explored.

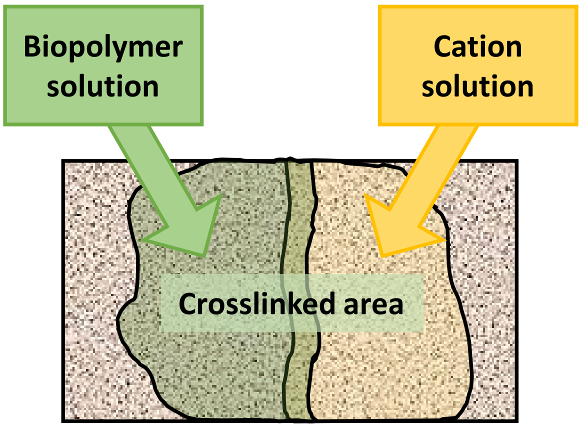


Fig. 8 Illustration of multi-channel crosslinked-biopolymer injection

5. CONCLUSIONS

Biopolymer injection has a significant potential of being implemented. Among other polysaccharide biopolymers, xanthan gum has proven to be most practical host as it can be easily controlled throughout the process, unlike thermal-based biopolymers. Based on the studies, the key to successful integration of biopolymer and injection method is controlling biopolymer's injectability through viscosity optimization. Viscosity of biopolymer, which can be controlled through biopolymer to water mix ratio by mass, influences injectability and penetrability. Higher concentration leads to higher viscosity of hydrogel which makes it harder to be injected and distributed. Hence, higher pressure and flow rate is required for a more viscous biopolymer hydrogel. Further study regarding this topic is highly demanded as there are many potentials yet to be unveiled.

Crosslinked biopolymer injection should be studied deeper as crosslinking application can further improve this integration. With multi-channel injection, the reviewed pressure of 400kPa for biopolymer injection can still be utilized as the biopolymer and crosslinker have their own channel allowing crosslinked biopolymer injection flexibly and handful crosslink possibilities.

ACKNOWLEDGEMENT
This work was supported by the National Research Foundation of Korea (NRF) grant funded by the Korea government. (MSIT) (2023R1A2C300559611).

REFERENCES
Ahearn, G. P. (1969), "Surfactants for oil recovery", *Journal of the American Oil Chemists' Society*, **46**, 540A-582A.
Ayeldeen, M., Negm, A., El-Sawwaf, M., & Kitazume, M. (2017), "Enhancing mechanical behaviors of collapsible soil using two biopolymers", *Journal of rock mechanics and geotechnical engineering*, **9** (2), 329-339.
Chang, I., Im, J., Prasidhi, A. K., & Cho, G. C. (2015a), "Effects of Xanthan gum biopolymer on soil strengthening", *Construction and Building Materials*, **74**, 65-72.
Chang, I., Prasidhi, A. K., Im, J., & Cho, G. C. (2015b), "Soil strengthening using thermo-gelation biopolymers", *Construction and Building Materials*, **77**, 430-438.
Chang, I., Im, J., & Cho, G. C. (2016a), "Geotechnical engineering behaviors of gellan gum biopolymer treated sand", *Canadian Geotechnical Journal*, **53** (10), 1658-1670.
Chang, I., Im, J., & Cho, G. C. (2016b). Introduction of microbial biopolymers in soil treatment for future environmentally-friendly and sustainable geotechnical engineering. Sustainability, **8** (3), 251.
Chang, I., Lee, M., Tran, A. T. P., Lee, S., Kwon, Y. M., Im, J., & Cho, G. C. (2020), "Review on biopolymer-based soil treatment (BPST) technology in geotechnical engineering practices", *Transportation Geotechnics*, **24**, 100-385.
Clinckspoor, K. J., Sousa-Ferreira, V. H. D., & Barros-Zanoni-Lopes-Moreno, R. (2021), "Bulk rheology characterization of biopolymer solutions and discussions of their potential for enhanced oil recovery applications", *CT&F-Ciencia, Tecnología y Futuro*, **11**(1), 123-135.
Falihah, M., Gang, S., Ryou, J. E., Hong, W. T., & Jung, J. (2025), "Penetration Lengths of Agar Gum and Gellan Gum Used for Injection Grouting into Porous Media at Different Pressures", *Journal of Geotechnical and Geoenvironmental Engineering*, **151** (4), 04025011.
Feng, X., Wu, K. W., Balajee, V., Leissa, J., Ashraf, M., & Xu, X. (2023), "Understanding syringeability and injectability of high molecular weight PEO solution through time-dependent force-distance profiles", *International Journal of Pharmaceutics*, **631**, 122486.
Im, J., Chang, I., & Cho, G. C. (2021), "Effects of malonic acid crosslinked starch for soil strength improvement", *Transportation Geotechnics*, **31**, 100653.
Khattab, H., Gawish, A. A., Hamdy, A., Gomaa, S., & El-Hoshoudy, A. N. (2024), "Assessment of a novel xanthan gum-based composite for oil recovery improvement at reservoir conditions; Assisted with simulation and economic studies", *Journal of Polymers and the Environment*, **32** (7), 3363-3391.
Kwon, Y. M., Moon, J. H., Cho, G. C., Kim, Y. U., & Chang, I. (2023), "Xanthan gum biopolymer-based soil treatment as a construction material to mitigate internal erosion

of earthen embankment: A field-scale", *Construction and Building Materials*, **389**, 131716.

Lee, M., Im, J., Chang, I., & Cho, G. C. (2021), "Evaluation of Injection capabilities of a biopolymer-based grout material", *Geomechanics and Engineering,* **25** (1), 31-40.

Lee, M., Chang, I., Kang, S. J., Lee, D. H., & Cho, G. C. (2023a), "Alkaline induced-cation crosslinking biopolymer soil treatment and field implementation for slope surface protection", *Geomech. Eng*, **33** (1), 29-40.

Lee, M., Park, D. Y., Kwon, Y. M., Chang, I., & Cho, G. C. (2023b), "Study on crosslink-induced gelation of xanthan gum biopolymer and its soil strengthening behavior as sustainable grout material", *Geo-Congress 2023*, 322-330.

Lee, M., Chang, I., & Cho, G. C. (2025), "Hydraulic erosion mitigation in sandy soil using cation-crosslinked gelation biopolymer", *Acta Geotechnica*, 1-18.

Lipton, Daniel. (1974), "Improved Injectability of Biopolymer Solutions", *Fall Meeting of the Society of Petroleum Engineers of AIME*.

Park, D. Y., Chang, I., Lee, M., & Cho, G. C. (2025), "Enhancing soil liquefaction resistance and small-strain dynamic properties using cation-crosslinked biopolymer hydrogel", *Soil Dynamics and Earthquake Engineering*, **190**, 109212.

Ruel-Gariépy, E., & Leroux, J. C. (2004), "In situ-forming hydrogels—review of temperature-sensitive systems", *European Journal of Pharmaceutics and Biopharmaceutics*, **58** (2), 409-426.

Ryou, J. E., & Jung, J. (2023), "Characteristics of thermo-gelation biopolymer solution injection into porous media", *Construction and Building Materials*, **384**, 131451.

Soldi, V. (2004), "Stability and degradation of polysaccharides", *Polysaccharides: Structural diversity and functional versatility*, 395-409.

Stojkov, G., Niyazov, Z., Picchioni, F., & Bose, R. K. (2021), "Relationship between structure and rheology of hydrogels for various applications", *Gels*, **7**(4), 255.

Tran, A. T. P., Chang, I., & Cho, G. C. (2019), "Soil water retention and vegetation survivability improvement using microbial biopolymers in drylands", *Geomech. Eng*, **17**(5), 475-483.

Vinoth, G., Moon, S. W., Moon, J., & Ku, T. (2018), "Early strength development in cement-treated sand using low-carbon rapid-hardening cements", *Soils and Foundations*, **58** (5), 1200-1211.

Wiszniewski, M., Skutnik, Z., & Cabalar, A. F. (2013), "Laboratory assessment of permeability of sand and biopolymer mixtures", *Annals of Warsaw University of Life Sciences-SGGW. Land Reclamation*, **45** (2).

Xuewu, Z., Xin, L., Dexiang, G., Wei, Z., Tong, X., & Yonghong, M. (1996), "Rheological models for xanthan gum", *Journal of Food Engineering*, **27** (2), 203-209.

Yegin, C., Singh, B.P., Zhang, M., Biopharm, F., Balaji, K., Suhag, A., Ranjith, R., Peksaglam, Z., Wijaya, Z., Putra, D. & Anggraini, H. (2017), "Next-generation displacement fluids for enhanced oil recovery", *SPE Oil and Gas India Conference and Exhibition,* D021S010R001.

DATABASE/REGULATORY SOURCE

Clarivate. (2025), *Web of Science*, retrieved from https://www.webofscience.com.

U.S. Food and Drug Administration. (2025), "Food Additive Status List", retrieved from https://www.fda.gov/food/food-additives-petitions/food-additive-status-list.

US Geological Survey. (2025), “Cement prices in the United States from 2010 to 2024 (in U.S. dollars per metric ton)”, *Statista*, retrieved from https://www.statista.com/statistics/219339/us-prices-of-cement/.

US Geological Survey. (2025), “Production volume of cement worldwide from 1995 to 2024 (in billion metric tons)”, *Statista*, retrieved from https://www.statista.com/statistics/1087115/global-cement-production-volume/.