Proceedings of the 21st ICSMGE, Vienna, Austria, 14 – 19 June 2026. Pistrol, Adam & Schweiger (eds.)
Published by: ÖGG, Austrian Society for Geomechanics, Salzburg, Austria, ISBN 978-3-9503898-4-5
https://doi.org/10.53243/ICSMGE2026-2324

Soil improvement mechanism using biomass-derived polymers based on soil mechanics and reproduction of the mechanical behavior of improved soil

Takayuki Sakai
Nagoya University, Nagoya, Japan, t-sakai@civil.nagoya-u.ac.jp

ABSTRACT: Recently, biomass-derived polymers have been increasingly considered as eco-friendly additives and modifiers for various construction materials; however, the mechanical behavior of such systems is poorly understood. This study investigates the effectiveness of soil improvement and its mechanical behavior using biopolymers, specifically chitosan (CS) and carboxymethyl cellulose (CMC). Laboratory tests were conducted on specimens prepared with varying degrees of compaction (Dc = 75% and 90%) and CS:CMC mixing ratios (1:1 and 2:1). The effects of biopolymer treatment were examined based on soil mechanics principles. In the oedometer tests, specimens with higher CS:CMC ratios exhibited greater consolidation yield stress and compressibility. In the triaxial compression tests, a higher CS:CMC ratio led to more pronounced hardening with plastic expansion and improved shear strength, suggesting an increase in overconsolidation ratio (OCR). Furthermore, the addition of biopolymers altered not only the soil skeleton structure but also fundamental physical properties such as the liquid limit and compression index, indicating a change in the type of soil itself. The upward shift of the normal consolidation line (NCL) caused by biopolymer treatment contributes to an increased OCR. The elasto-plastic constitutive model, SYS Cam-clay model, successfully reproduced the mechanical behavior of polymer-improved soils. Polymer treatment increases the OCR and increasing the density of improved soils also leads to a higher OCR and structural degradation similar to unimproved soils. These findings provide important insights into the mechanisms of biopolymer-based soil improvement from a geotechnical perspective, enabling the design of more efficient and sustainable soil reinforcement systems.

KEYWORDS: Biopolymer, Ground improvement, Triaxial compression test, Oedometer test, Constitutive model.

1 INTRODUCTION

In recent years, the addition of polymeric materials has emerged as a method for ground improvement. For instance, during the Chernobyl nuclear disaster, solid polymer ion complexes (polyion complexes, or PICs) were utilized to prevent the spread of radioactive substances in contaminated soils (Zezin et al, 2015). Similarly, in the Fukushima Daiichi nuclear accident caused by the Great East Japan Earthquake, polymeric materials blended with soil were used as selective separation aids for contaminated soil (Kumazawa, 2011). Strong electrostatic interactions between positively charged polymers (polycations) and negatively charged polymers (polyanions) results in the formation of PICs (Figure 1, top) that binds with soil particles, thereby immobilizing the soil and radioactive contaminants (Figure 1, bottom). Over the past few decades, PICs have also been actively studied as soil conditioners in the field of agriculture (Zezin et al, 2015; Izumrudov et al, 2019; Panova et al, 2021). In our previous studies, we also attempted ground improvement using chitosan (CS) as the polycation and carboxymethyl cellulose (CMC) as the polyanion, and evaluated the effectiveness through unconfined compression tests. As a result, increased unconfined compressive strength was observed for three types of soils—clay, sand, and Masado soil (Zincheko et al, 2022). Furthermore, the improved soils demonstrated sufficient durability in terms of biodegradability (Wang et al, 2024).

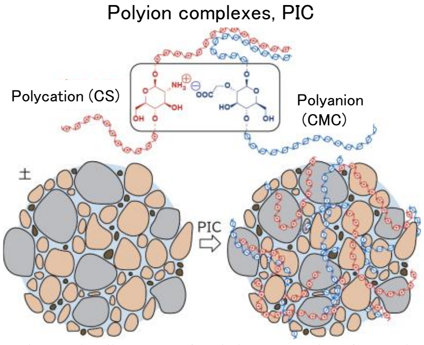

Figure 1. Schematic diagram of polyion complex formation.

In many of these studies, strength evaluations such as unconfined compression tests or simple shear tests were conducted, primarily on clay or sand (Chang et al, 2020; Fatehi, et al, 2021). Only a limited number of studies have employed triaxial compression tests to capture the detailed mechanical behavior of polymer-treated soils. Moreover, real ground structures are often built using intermediate soils composed of various particle sizes, ranging from gravel to clay. Therefore, it is necessary to conduct experiments using intermediate soils when aiming for practical applications.

Based on the aforementioned background, this study places particular emphasis on clarifying the mechanical behavior and improvement mechanisms of biopolymer-improved intermediate soils. The objectives of this study are twofold: (1) to investigate in detail the mechanical properties of intermediate soils improved with biopolymers; (2) to consider the mechanical behavior and improvement mechanisms of polymer-treated soils based on soil mechanics theory and the concept of soil skeleton structure; (3) reproduce the mechanical behavior of improved soil by constitutive model. To achieve these objectives, this study investigates the improvement of masado soil, which contains a mixture of coarse and fine particles, using biomass-derived polymers. The same CS–CMC improvement method employed in the previous study (Zinchenko et al, 2022), and the same method is adopted in this study. Both CS and CMC are naturally occurring polymers that are available at low cost, making them suitable for large-scale industrial applications and well-aligned with the goals of carbon neutrality and a circular economy. The improved soils were evaluated for physical properties such as liquid and plastic limits, as well as compressibility through oedometer tests and shear strength through undrained triaxial tests. The effectiveness of polymer treatment was further analyzed based on soil mechanics to clarify the improvement mechanisms. Finally, the mechanical results were reproduced by SYS Cam-clay model (Asaoka et al, 2002), which introduces the skeletal structure concept into the modified Cam-clay model (Roscoe and Burland, 1968).

2 THE MATERIAL USED IN THE EXPRERIMENTS

Figure 2 shows the grain size distribution of the soil. The coefficient of uniformity (Cu) was 39.3, and the coefficient of curvature (Cc) was 3.75. The soil particle density ρ_s was 2.716 g/cm^3. The maximum dry density ρ_{dmax} was 1.864 g/cm^3 and the optimum water content w_{opt} was 13.5% from compaction test using the A-b method.

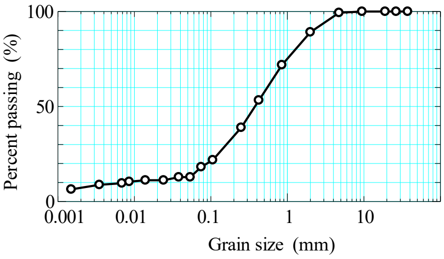

Figure 2. Grain size distribution.

Chitosan is a naturally derived polymer obtained by deacetylating chitin—found in the shells of crustaceans such as shrimp and crabs, as well as in the exoskeletons of insects and the shells and tissues of mollusks—through treatment with an alkaline aqueous solution. Due to its low cost, abundance, biocompatibility, and high biodegradability, chitosan has been widely applied in the development of wound dressings, bioadhesives, and biodegradable plastics (Ishihara et al, 2002). In this study, chitosan with a molecular weight of 50,000–190,000 g/mol and a degree of deacetylation of 75–85% was used.

Carboxymethyl cellulose is an anionic water-soluble polymer derived from cellulose ($(C_6H_{10}O_5)_n$) by introducing carboxymethyl groups ($-CH_2COOH$), thereby rendering the originally water-insoluble cellulose soluble. CMC exhibits excellent thickening, water absorption, and water retention properties. As it is derived from natural cellulose, it possesses moderate biodegradability and can be incinerated after use. In this study, CMC with a molecular weight of 700,000 g/mol was dissolved in water and used as an aqueous solution.

3 SPECIMEN PREPARATION AND TEST PROCEDURE

3.1 *Specimen Preparation*

The specimen preparation processes are shown below.

1. Masado soil was sieved using 2 mm and 250 µm sieves to classify it into three particle size ranges. The dry mass of each fraction was then measured based on the grain size distribution curve shown in Figure 2. The total mass of the specimen was calculated using the target water content and degree of compaction, identical to those used for the untreated soil, even in the case of polymer treatment.
2. A 1% aqueous solution of carboxymethyl cellulose (CMC) and the prescribed amount of powdered chitosan (CS) were placed into a beaker. Glucono delta-lactone (GDL) powder was added as a pH adjuster, and the mixture was stirred at 1000 rpm for 5 minutes using a small-scale mixer.
3. The prescribed amount of masado soil and the polymer mixture were thoroughly mixed. The mixture was compacted in three layers into a mold with a height of 10 cm and an inner diameter of 5 cm by free-fall ramming, so that each layer reached one-third of the mold height. This process ensured uniformity and achieved the target density.
4. To maintain the water content, the mold was sealed with plastic wrap and cured for one week in a dark, temperature-controlled chamber maintained at 20 °C.

3.2 *Improved soil used in tests*

Table 1 summarizes the properties of the polymer-improved soil in this study. The specimens were prepared by varying the mixing ratio of chitosan (CS) and carboxymethyl cellulose (CMC), and the degree of compaction (Dc). Table 1 presents the mixing ratios of CS and CMC, Dc, and the mass of CS and CMC added in each case. Additionally, the dry weight ratio of soil to polymer (SPR) is also listed. The water content was 15.6% for all specimens.

Table 1. The properties of the polymer-improved soil.

Case	CS:CMC	CS (g)	CMC (g)	SPR (%)	D_c (%)
Dc90-umimproved	-	-	-	-	90
Dc90-1:1	1:1	0.54	0.54	0.33	90
Dc90-2:1	2:1	1.08	0.54	0.49	90
Dc75-umimproved	-	-	-		75
Dc75-1:1	1:1	0.44	0.44	0.33	75
Dc75-2:1	2:1	0.87	0.44	0.49	75

3.3 *Test procedure*

The liquid limit and plastic limit tests were conducted for specimens with a degree of compaction Dc = 75%. The tests were not performed for Dc = 90%, based on the assumption that identical results would be obtained if the same Soil Polymer Ratio (SPR) was used. After curing, the specimens were removed from the molds, thoroughly kneaded on a glass plate, and tested in accordance with JIS A 1205.

The triaxial compression tests were conducted in accordance with JGS0523-2009. After placing the specimen in the triaxial test apparatus, saturation was achieved using the double suction method and back pressure method. Once a B-value of 95% or greater was confirmed, isotropic consolidation was conducted at an effective confining pressure p' = 100kPa until the volumetric strain converged. Then, undrained shear testing was conducted at a shear rate of 0.014 mm/min.

The oedometer tests were conducted according to JIS A 1217 using the incremental loading method. Specimens were prepared by compacting a single layer of soil using a rammer in a consolidation ring with a height of 2 cm and a diameter of 6 cm. After curing, the specimens were placed into the consolidation apparatus, submerged in water, and left to stand for 24 hours before loading was applied.

4 TEST RESULTS

4.1 *Liquid Limit and Plastic Limit Tests*

Table 2 summarizes Liquid and Plastic Limit test results. The base soil was classified as NP (non-plastic) based on the test results. However, the addition of polymer materials enabled to get both the liquid limit and plastic limit. It was observed that both limits increased as the CS:CMC ratio increased. This is attributed to the water absorption and retention properties of the reacted polymer materials, which became more prominent with higher additive amounts. Several previous studies have also reported increases in the liquid limit upon the addition of polymer materials (Nugent et al, 2009; Chen et al, 2013).

Table 2. The properties of the polymer-improved soil.

CS:CMC	umimproved	1:1	2:1
Liquid Limit w_L	NP	38.8	52.5
Plastic Limit w_P	NP	31.1	39.9

4.2 *Oedometer test*

Figure 3 and 4 show the results for specimens compacted to Dc = 75% and 90 %, respectively. The compression lines were changed by the addition of polymer materials, and the degree of change varied depending on the amount added. From Figure. 4, compared to untreated soil, the addition of polymer materials increases the consolidation yield stress and causes the compression lines to shift upward. In addition, for specimens with Dc = 75%, the amount of compression is larger than that for Dc = 90%, due to the lower density. Overall, as the CS:CMC ratio increases, the consolidation yield stress increases, and the amount of compression after yielding also becomes larger. These trends were confirmed to be independent of Dc. Increases in consolidation yield stress have been reported in the literature (Joga et al, 2019; Chang et al, 2020), while increases in compressibility have been confirmed in literature (Kumar et al, 2023).

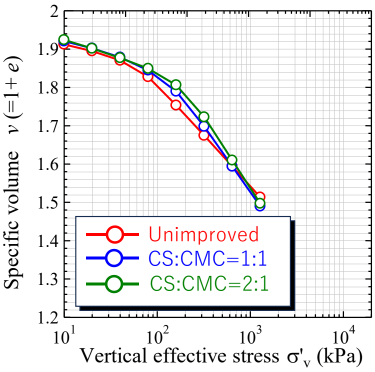

Figure 3. The oedometer test results (Dc = 75%).

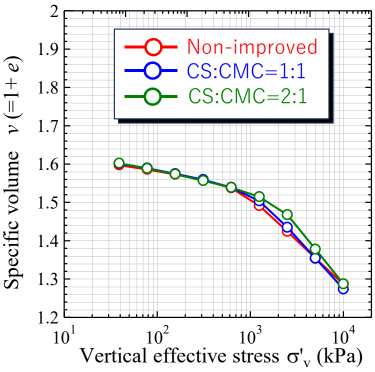

Figure 4. The oedometer test results (Dc = 90%).

4.3 *Triaxial compression test*

Figures 5 and 6 show the results for specimens compacted to Dc = 75% and 90 %, respectively. From the q-ε_a relationships in Figures 5 and 6, increasing the CS:CMC ratio leads to greater strain hardening and a higher final deviator stress q.

Focusing on the p'-q diagrams, assuming the state at the end of shearing to be the critical state and plotting a line $q = Mp'$ (critical state line), the results were all M=1.5. In the Dc = 90% cases, all specimens exhibited a hardening behavior with plastic compression at the early stages of shearing, indicated by increasing q with decreasing p'. After reaching the critical state line, the specimens showed further hardening with plastic expansion, indicated by increasing q with increasing p'. In the Dc = 75% cases, all specimens initially exhibited hardening with plastic compression. For Non-improved soil, the stress state remained almost unchanged after reaching the critical state line. In contrast, polymer-improved soils exhibited hardening with plastic dilation was observed after reaching the critical state. Focusing on the CS:CMC ratio, the extent of initial plastic compression decreased as the ratio increased, while the degree of hardening with plastic expansion after reaching the critical state increased with a higher CS:CMC ratio.

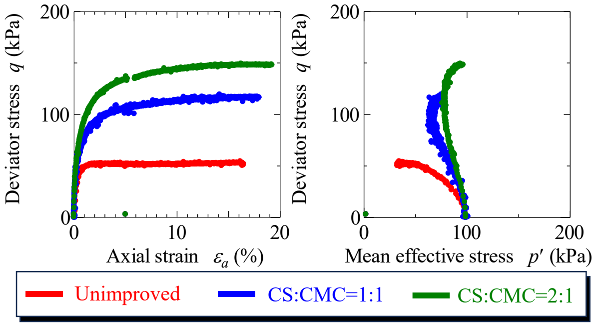

Figure 5. Undrained triaxial compression test results (Dc = 75%).

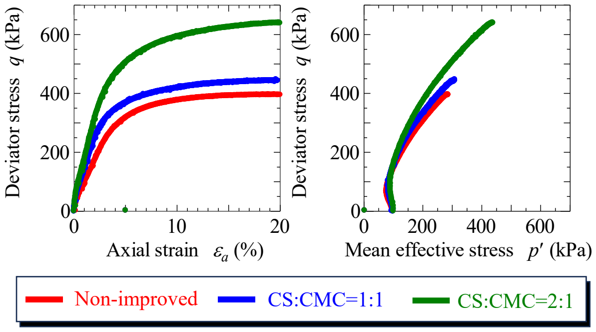

Figure 6. Undrained triaxial compression test results (Dc = 90%).

5 MECHANISM OF SOIL IMPROVEMENT BASED ON SOIL MECHANICS

From the mechanical behavior described in Section 4, it was shown that both the consolidation yield stress and the degree of hardening with plastic expansion increased. These behaviors can be interpreted as an increase in the overconsolidation ratio (OCR). To investigate the reason for the increase in overconsolidation ratio (OCR), additional consolidation tests were conducted under conditions where Dc = 75%, applying vertical stresses greater than those shown in Figure 3. The results are presented in Figure 7. As seen in Figure 7, the compression lines for CS:CMC = 2:1 and the unimproved soil intersect, indicating an increase in both the slope λ the intercept N of the compression line.

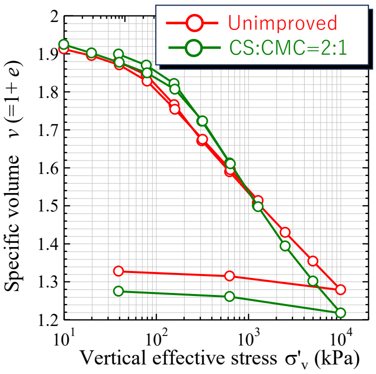

Figure 7. Additional consolidation test results (Dc = 75%).

Furthermore, as shown in Table 2, the addition of polymers also altered the liquid limit. Many studies have reported a correlation between the liquid limit and the compression index (Tiwari and Ajmera, 2011). In other words, a change in the liquid limit due to polymer addition implies a change in the compression index, suggesting that the compression lines of unimproved and improved soils are fundamentally different.

The improvement mechanism by polymer addition is explained based on soil mechanics using Figure 8. Addition of polymers to soil makes the slope and intercept of the Normal Consolidation Line (NCL) increase. As shown in Figure 8, the NCL shifts rightward and upward due to polymer addition. Therefore, the soil in initial condition obtains higher overconsolidation ratio (OCR) : the OCR for unimproved soil is $\sigma'_{\mathrm{v1}}/\sigma'_{\mathrm{v0}}$, while for improved soil it is $\sigma'_{\mathrm{v2}}/\sigma'_{\mathrm{v0}}$.

This supports the test results obtained from the oedometer test and the triaxial test, which indicate that the polymer-treated soil exhibits the behavior of overconsolidated soil.

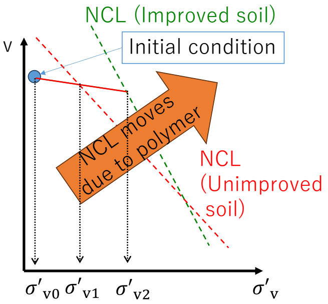

Figure 8. Additional consolidation test results (Dc = 75%).

6 REPRODUCTION OF MECHANICAL BEHAVIOR OF POYMER IMPROVED SOIL

The SYS Cam-clay model is an elasto-plastic constitutive model, which describes the mechanical behavior of structured and overconsolidated soils. For further details, please refer to the studies by Asaoka et al. (2002). The soil skeleton structure is interpreted based on structure, overconsolidation, and anisotropy. A key feature of the model is that the model can describe the mechanical behavior of typical clays, sands, intermediate soils, and problematic soils within a same framework by controlling the rate of skeleton structure evolution associated with plastic deformation through “evolution laws”. For example, clean sands exhibit rapid structural degradation and slow loss of overconsolidation, while naturally deposited clays show fast loss of overconsolidation and slow structural degradation.

In this section, the experimental results presented in the section 4 is reproduced using the SYS Cam-clay model to provide further discussion on the improvement mechanism. Figures 9 through 12 show the results of the simulations, while Table 3 summarize the material constants and Tables 4 and 5 initial values obtained through the reproductions.

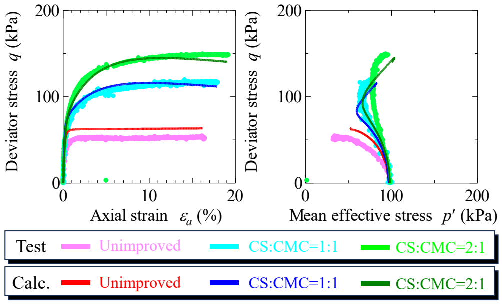

Figure 9. Reproduction results of triaxial compression test (Dc = 75%).

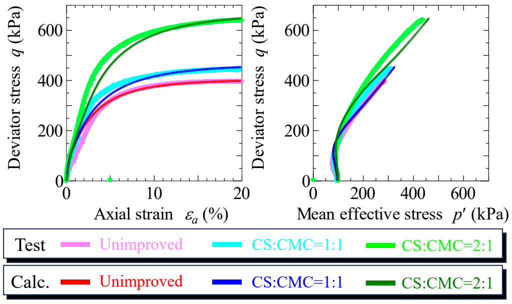

Figure 10. Reproduction results of triaxial compression test (Dc = 90%).

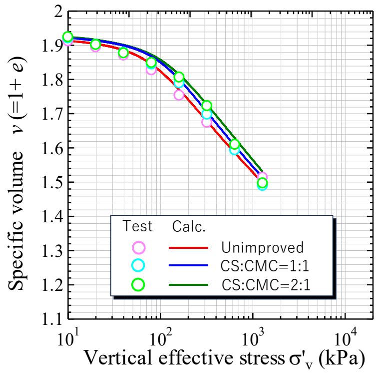

Figure 11. Reproduction results of oedometer test (Dc = 75%).

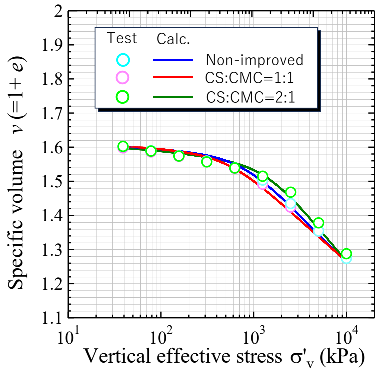

Figure 12. Reproduction results of oedometer test (Dc = 90%).

Table 3. Material constant.

Material	unimproved	CS:CMC 1:1	CS:CMC 2:1
Compression index	0.100	0.115	0.130
Swelling index		0.010	
Critical state index		1.500	
NCL intercept (at p' = 98.1 kPa)	1.700	1.760	1.820
Poisson’s ratio		0.15	
Normal consolidation index		0.80	
Structure decay index (b=c=1)		0.50	
Ratio of $\left\|\mathbf{D}_s^p\right\|$ to $-D_v^p$		0.20	
Rotational hardening index		0.010	
Rotational hardening limit constant		1.00	

Table 4. Initial condition of triaxial compression test.

	Dc75-unimproved	Dc75 1:1	Dc75 2:1
Overconsolidation Ratio	1.0	7.0	10.0
Degree of structure	1.1	3.4	3.5
Specific Volume	1.868	1.868	1.901
Mean effective stress (kPa)	20.0	20.0	20.0
	Dc90-unimproved	Dc90 1:1	Dc90 2:1
Overconsolidation Ratio	35.0	44.0	55.0
Degree of structure	1.0	1.1	1.3
Specific Volume	1.543	1.579	1.574
Mean effective stress (kPa)	20.0	20.0	20.0

Table 5. Initial condition of oedometer test.

	Dc75-unimproved	Dc75 1:1	Dc75 2:1
Overconsolidation Ratio	8.0	10.0	12.0
Degree of structure	3.0	3.7	3.8
Specific Volume	1.912	1.921	1.924
Mean effective stress (kPa)	10.0	10.0	10.0
	Dc90-unimproved	Dc90 1:1	Dc90 2:1
Overconsolidation Ratio	15.0	22.0	40.0
Degree of structure	1.8	1.9	2.3
Specific Volume	1.602	1.608	1.597
Mean effective stress (kPa)	39.2	39.2	39.2

In the SYS Cam-clay model, differences in material constants reflect differences in soil type. In this study, it was assumed that soils with the same ratio soil to polymer (SPR), as listed in Table 1, have the same material constants regardless of compaction degree. In addition, except for the compression index λ and the intercept of the NCL, all other material constants were assumed to be unchanged by polymer treatment. The initial values represent the initial state of the specimen, and variations in density are reflected solely through differences in these initial values.

As shown in Figures 9 through 12, the simulation results reproduced the experimental behavior, demonstrating that the SYS Cam-clay model can describe the mechanical behavior of polymer-improved soils.

From the material constants in Table 3, the structure decay index is smaller than the Normal consolidation index, indicating that the material tends to dissipate overconsolidation more readily than to decay structure.

Regarding the initial values in Tables 4 and 5, the overconsolidation ratio increased due to polymer improvement. Moreover, specimens with a CS:CMC ratio of 2:1 exhibited a higher OCR than those with a ratio of 1:1, consistent with the experimental findings. Additionally, specimens compacted to Dc =90% showed a smaller degree of structure and a higher OCR compared to those compacted to Dc =75%, due to the higher compaction energy.

7 CONCLUSIONS

The conclusions are shown below.

1) The base soil was classified as NP (non-plastic) based on the test results. However, the addition of polymer materials enabled to get both the liquid limit and plastic limit.
2) The addition of CS and CMC increased the yield stress regardless of the degree of compaction, and the amount of compression also became larger. The compression line shifted upward.
3) The results of undrained triaxial compression tests showed that, regardless of the degree of compaction, higher CS:CMC ratios led to increased shear strength and more pronounced strain hardening with plastic dilatancy.
4) The compression line of improved soil crossed with that of untreated soil. This finding and conclusion 1) indicate that the addition of biopolymers increased both the intercept and slope of the NCL. Even under the same degree of compaction, shift of NCL resulted in an increased overconsolidation ratio (OCR), leading to a higher yield stress and more pronounced hardening behavior with plastic expansion during shearing.
5) The elasto-plastic constitutive model, SYS Cam-clay model, successfully reproduced the mechanical behavior of polymer-improved soils. Polymer treatment increases the OCR and increasing the density of improved soils also leads to a higher OCR and structural degradation similar to unimproved soils.

8 ACKNOWLEDGEMENTS

The author would like to express their sincere gratitude to Professor Zinchenko and Professor Nakano of Nagoya University for their valuable guidance and support in conducting the experiments. The author also thank N. Takeda and S. Fukumoto, former students at Nagoya University, for their great contribution to this research.

9 REFERENCES

Asaoka, A., Noda, T., Yamada, E., Kaneda, K. and Nakano, M. 2002. An elasto-plastic description of two distinct volume change mechanisms of soils. *Soils and Foundations* 42(5), 47-57.

Chang, I., Lee, M., Tran, A.T.P., Lee, S., Kwon, Y.M., Im. J. and Cho, G.C. 2002. Review on biopolymer-based soil treatment (BPST) technology in geotechnical engineering practices, *Transportation Geotechnics* 24, 100385

Chen, R., Zhang, L., Budhu, M. 2013. Biopolymer stabilization of mine tailings, *Journal of Geotechnical and Geoenvironmental Engineering*, 139, 1802-1807

Fatehi, H., Ong, D.E.L., Yu, J. and Chang, I. 2021. Biopolymers as Green Binders for Soil Improvement in Geotechnical Applications: A Review, *Geosciences*, 11(7), 291.

Ishihara, M., Nakanishi, K., Ono, K., Sato, M., Kikuchi, M., Saito, Y., Yura, H., Matsui, T., Hattori, H., Uenoyama, M. and Kurita, A. 2002. Photocrosslinkable chitosan as a dressing for wound occlusion and accelerator in healing process, *Biomaterials*, 23(3), 833-840.

Izumrudov, V.A., Mussabayeva, B.K., Kassymova, Z.S., Klivenko, A.N. and Orazzhanova, L.K. 2019. Interpolyelectrolyte complexes: advances and prospects of application, *Russian Chemical Reviews* 88(10), 1046-1062.

Joga, J.R. and Varaprasad, B. 2019. Sustainable Improvement of Expansive Clays Using Xanthan Gum as a Biopolymer. *Civil Engineering Journal* 5, 1893-1903.

Kumazawa, N. 2011. From the decontamination site in Iitate village - What should chemists do now? Toward the decontamination of radioactive materials caused by the Fukushima Daiichi Nuclear Power Station accident., Chemistry Today, 484, 34-38 (in Japanese).

Kumar, S.A., Sujatha, E.R., Pugazhendi, A. and Jamal, M.T. 2023. Guar gum-stabilized soil: a clean, sustainable and economic alternative liner material for landfills, *Clean Technologies and Environmental Policy* 25, 323-341.

Nugent, R.A., Zhang, G. and Gambrell, R.P. 2009. Effect of exopolymers on the liquid limit of clays and its engineering implications, *Transportation Research Record*, 2101, 34-43.

Panova, I.G., Demidov, V.V., Shulga, P.S., Ilyasov, L.O., Butilkina, M.A. and Yaroslavov, A.A. 2021. Interpolyelectrolyte complexes as effective structure-forming agents for Chernozem soil, *Land Degradation & Development* 32(2), 1022-1033.

Roscoe, K.H., Burland, J.B. 1968. On the generalized stress-strain behavior of 'wet' clay. Engineering Plasticity (ed. By Hey-man, J. and Leckie, F. A.), *Cambridge University Press*, 535-609

Tiwari, B. and Ajmera, B. 2011. Consolidation and swelling behavior of major clay minerals and their mixtures, *Applied Clay Scienece*, 54, 264-273.

Wang, Y., Sakai, T., Shibata, N., Zinchenko, A. and Nakano, M. 2024. Soil improvement by biomass polyions and compaction: Reinforcement, biodegradation resistance, and retention of heavy metal ions, *Journal of Environmental Chemical Engineering* 12(1), 111676.

Zezin, A.B., Mikheikin, S.V., Rogacheva, V.B., Zansokhova, M.F., Sybachin, A.V. and Yaroslavov, A.A. 2015. Polymeric stabilizers for protection of soil and ground against wind and water erosion, *Advances in Colloid and Interface Science* 226, 17-23.

Zinchenko, A., Sakai, T., Morikawa, K. and Nakano, M. 2022. Efficient stabilization of soil, sand, and clay by a polymer network of biomass-derived chitosan and carboxymethyl cellulose, *Journal of Environmental Chemical Engineering* 10(1), 107084.