Improvement of soil mechanical properties by biomass-derived chitosan and carboxymethyl cellulose

T. Sakai & M. Nakano
Nagoya University, Nagoya, Aichi, Japan

ABSTRACT: In order to investigate the effectiveness of ground improvement methods using chitosan (CS) and carboxymethyl cellulose (CMC), which are biomass-derived polymeric materials, unconfined compression test and triaxial compression test were conducted on specimens compacted after mixing CS and CMC with soil. The results showed that the improved soil had much greater strength than the untreated soil. The dilatancy properties were also found to be different, suggesting that the critical state constant was different. The greater the concentration of CMC solution, the greater the strength; and the most effective mass ratio of CS to CMC was 2 to 3 times CS to CMC.

1 INTRODUCTION

Polymeric materials have been widely used to solve various environmental problems. Solid polymer-ion complexes (polyion complexes, PIC) were used to prevent the dispersion of radioactive materials in soil contaminated by the nuclear power plant accident in Chernobyl (Zezin et al., 2015). In the Fukushima nuclear power plant accident, PIC were used to immobilize the soil surface layer and to detach soil contaminated with radioactive cesium (Kumazawa, 2011). The mechanisms of soil immobilization of contaminants are as follows. Strong electrostatic interactions between positively charged polymers (polycations) and negatively charged polymers (polyanions) form PIC (Figure 1, top). In the soil, PIC polymers further bind to soil particles, immobilizing the soil and radioactive materials (Figure 1, bottom). PIC have been actively explored as soil improvement formulations in the agricultural field during several past decades (e.g., Izumrudov et al., 2019).

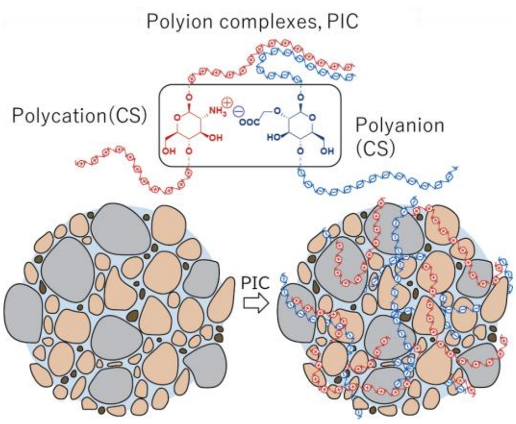

Figure 1. Schematic diagram of polyion complex formation.

In this study, chitosan (CS) was used as a polycation and carboxyl methyl cellulose (CMC) was used as a polyanion to improve soil. CS and CMC are naturally derived polymers and are low cost. Therefore, they are suitable for industrial-scale applications and satisfy the needs of "carbon neutral" and "circular economy". The soil improvement method proposed in this study using biomass-derived CMC and CS is a "green" and sustainable approach and is expected to be a more flexible soil improvement method compared to previous studies.

To investigate the effectiveness of soil improvement methods using CS and CMC, unconfined compression test and triaxial compression test were conducted on specimens compacted after mixing CS and CMC with soil. First, the mixing method of CS, CMC, and soil was investigated, and then the effects of CS and CMC concentrations on the strength were examined. The curing period of the specimens was also investigated.

2 EFFECT OF SAMPLE PREPARATION ON THE STRENGTH OF IMPROVED SOIL

Figure 2 shows the particle size distribution of the soils used in this study. 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. CS and CMC were mixed with 350 g dry weight of the soil in four methods. Method 1 is to add 0.7 g of CS powder and GDL solution, a pH adjuster, to 70 g of CMC solution and mix them before adding them to the soil. Method 2 is to add 35 g of CS solution to the soil and then mix it with 35 g of CMC solution. Method 3 is to add 35 g of CMC solution to the soil and then mix it with 35 g of CS solution. Method 4 is to first divide the soil into two parts and then mix the two parts with 35 g of CS solution and 35 g of CMC solution, respectively. In all of methods 1 through 4, 0.7 g of CS and 0.7 g of CMC were mixed.

The mixed sample were compacted in the mold in three layers using rammers to prepare the specimens. The density was adjusted to 90% of the maximum dry density, with a water content of approximately 20%. The specimens were cured in the mold for four days.

Figure 3 shows the results of unconfined compression tests conducted in accordance with JIS A 1216:2020. Figure 3 also shows the results for untreated soil adjusted to the same density and water content as the improved soil. Method 1 has the highest strength, with a compressive strength of approximately 140 kPa, about 1.5 times stronger than the other methods and three times stronger than the case with distilled water mixed in. The reason for the small strength in Methods 2-4 was assumed to be that soil particles had a negative charge and wasn't able to form a PIC well when mixed with CS, which had a positive charge in advance.

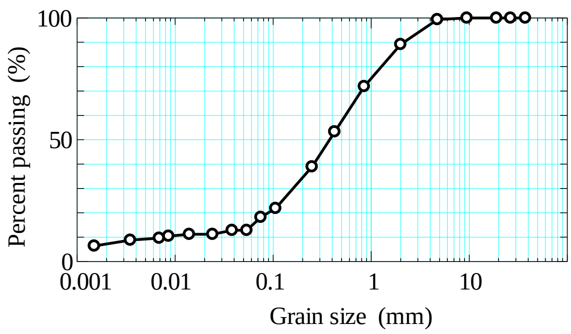

Figure 2. Grain size distribution.

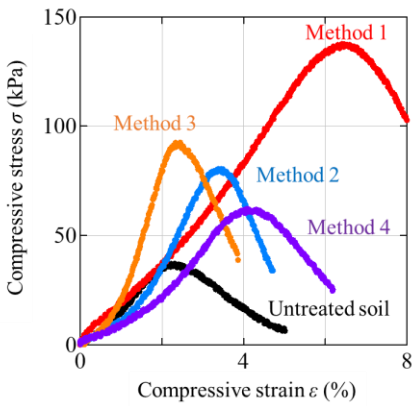

Figure 3. Effect of mixing method on the strength.

3 EFFECT OF CS AND CMC CONCENTRATIONS ON THE STRENGTH OF IMPROVED SOIL

All specimens in this and subsequent section were prepared by Method 1. In this section, specimens were prepared with varying concentrations of CMC and varying mixing ratios of CS and

CMC. Figure 4 shows the stress-strain relation for each case. In all cases, peak strength was observed at approximately 5-6% strain. The specimens with higher strength also had higher stiffness. The larger the concentration of CMC solution, the greater the unconfined compressive strength. On the other hand, the optimum ratio of CS to CMC changes depending on the concentration of CMC solution. The unconfined com-pressive strength of the soil was greater when CS is mixed more than CMC. This is be-cause soil particles have a negative charge, and it is important to mix more CS with a positive charge. The case of the highest strength was 560 kPa, which was about 10 times stronger than the untreated soil.

Curing periods were studied for cases with a CMC solution concentration of 1% and a CS:CMC ratio of 2:1. Four cases were tested: 4 days, 1 week, 2 weeks, and 3 weeks of curing after specimen preparation. For the curing method, the specimens were left in the mold, sealed to prevent drying, and left at room temperature. Figure 5 shows the strength increased up to 2 weeks of curing period, with the same strength at 2 and 3 weeks, indicating that 2 weeks of curing was sufficient for improvement. Because the increase in strength after 4 days of curing is not significant, it is possible to design the mix ratio of CS and CMC using specimens with a curing period of 4 days.

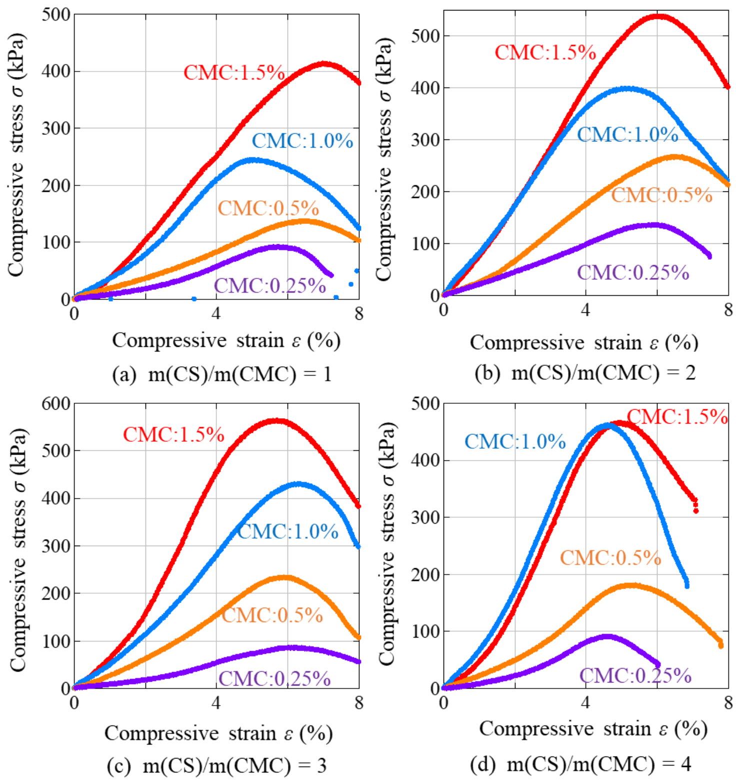

Figure 4. Unconfined compression test results of improved soil with different amounts of CMC and CS.

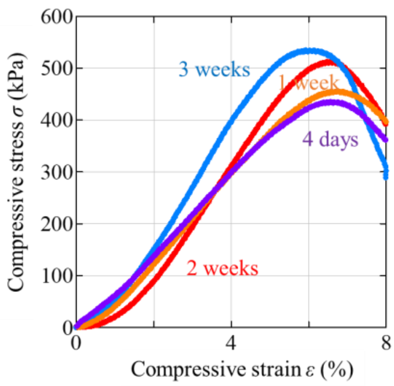

Figure 5. Effect of curing period.

4 TRIAXIAL COMPRESSION TEST FOR IMPROVED SOIL

Triaxial compression tests were conducted in accordance with JGS 0523-2020 with a CMC solution concentration of 1% and a CS:CMC ratio of 2:1. Untreated soil was also tested for comparison. The specimens were saturated using the double-suction and back-pressure method. After confirming that the B-value was larger than 0.95, isotropic consolidation was performed for 24 hours under a confining pressure of 100 kPa. Then, monotonic shear was applied at an axial strain rate of 20%/day under undrained condition.

Figure 6 shows the triaxial compression test results for improved soil and untreated soil. The two specimens were prepared at the same density. The relation between deviator stress q and axial strain ε_a shows that the maximum deviator stress was about 2.5 times higher than that of the untreated soil, even though the densities were the same. The untreated soil exhibited almost constant deviator stress after 5% axial strain ε_a, whereas the improved soil exhibited an increase in q with increasing ε_a. The q-mean effective stress p' relation indicated that the improved soil exhibited a remarkable hardening behavior with plastic expansion. The stress ratio ($\eta = q/p'$) at the transformation point and the η at ε_a of 20% were different, suggesting that the critical state index changes. The relation between excess pore water pressure u_e and ε_a showed that positive excess pore water pressure at the beginning of shear and negative excess pore water pressure at the end of shear for the improved soil were larger than ones for the untreated soil.

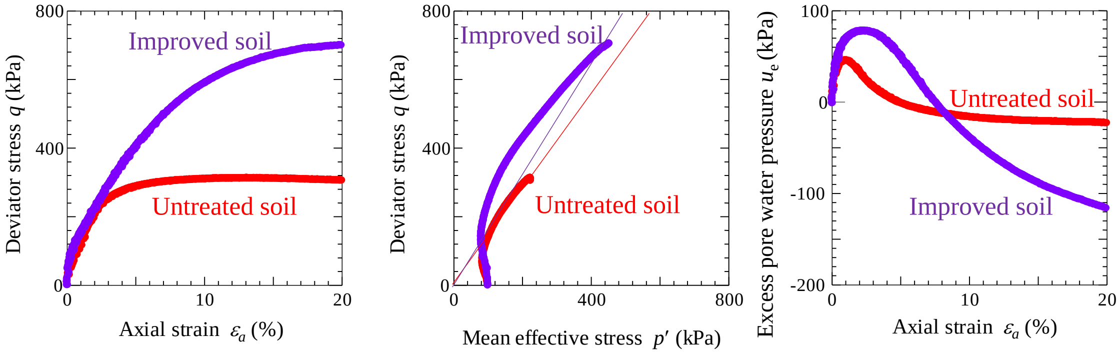

Figure 6. Triaxial compression test results for improved and untreated soil.

5 CONCLUSION

In this study, unconfined compression test and triaxial compression test were conducted on specimens compacted after mixing CS and CMC with soil to investigate the effectiveness of soil improvement methods using CS and CMC. The conclusions are as follows.

1) The most effective improvement was achieved by mixing the CMC solution with CS powder and GDL solution before mixing them with soil. In this method, the strength of the improved soil is clearly increased.
2) The larger the concentration of CMC, the greater the strength. The most effective mass ratio of CS to CMC also depends on the concentration of CMC; mixing two to three times as much CS as CMC was most effective. The greatest unconfined compressive strength of all cases was about 560 kPa, which was approximately 13 times greater than that of untreated soil.
3) The strength increased up to 2 weeks of curing period, with the same strength at 2 and 3 weeks, indicating that 2 weeks of curing was sufficient for improvement. Because the increase in strength after 4 days of curing is not significant, it is possible to design the mix ratio of CS and CMC using specimens with a curing period of 4 days.
4) Triaxial compression test results also indicated that the strength of the improved soil is much greater than that of the untreated soil. The dilatancy properties were also different. The stress ratio at the transformation point and ε_a of 20% were different, suggesting that the critical state index changed.

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