Deterioration of the bentonite sand mixture material due to thermal hydro chemical activity

Tomoyoshi Nishimura[1]

[1] Department of Civil Engineering, Ashikaga University, Tochigi, Japan

1 Introduction

Geoenvironmental engineering applications have attracted global attention. However, typical problems include complex multiphase interactions, which pose significant challenges from both a theoretical and technological perspective. Given the scientific challenges, a comprehensive study of the dissociation process is required to develop efficient hydrate-chemical methods. Although many experimental studies provide direct evidence, they are often constrained by environmental concerns, high technical demands, time-consuming procedures, and high costs. In contrast, numerical simulation models offer a more convenient predictive alternative because they are not limited by time, making them indispensable for advancing hydrate chemical development. Although the mechanical hydrate chemical dissociation process involves further complex Thermal-Hydraulic-Mechanical-Chemical (THMC) coupling among its four-component mixture (i.e., solid, water, gas, and hydrate phases), previous experimental tests have largely focused on coupled phenomena. Early experimental technical methods for unsaturated soil mechanics primarily incorporated controlling pore-water pressure, pore-air pressure, relative humidity, gas migration, and chemical solution applications. The soil water characteristic curve is the centre for interpreting the unsaturated soil properties using mathematical models. Furthermore, the evolution of salinity and carbonation due to the application of carbon dioxide pressure for addressing soil mechanical issues of geoenvironmental problems is lacking.

García and Hernández [1] reported that 21 derelict soils from a semi-arid Spanish Mediterranean area, with a lithological substrate of loams, submitted to a high degree of erosion, had several biological and biochemical properties (Gartner [2], Liu et al. [3], Raj et al. [4]). Zhu et al. [5] mentioned that interactions among vegetation, soil physical and chemical conditions, and soil microbial communities determine ecosystem functions, resilience, and stability. However, these interactions are still not fully understood in ecosystems. Bhatt and Arora [6] come out with a perfect intermediate tillage system that ultimately leads to sustainable agriculture. Bittelli et al. [7] mentioned that the quantification of soil evaporation and soil water content dynamics near the soil surface is critical in the physics of land-surface processes on regional and global scales, particularly in relation to mass and thermal energy fluxes between the ground and the atmosphere [8]. Gao and Shao [9] suggested that the accurate simulation of the effects of temperature on soil water movement processes is lacking in the study of hydrothermal interactions in soil systems. Previous research has proposed some potential mechanisms (e.g., surface tension-viscous flow) to explain soil hydraulic properties in relation to temperature, but little research has focused on temperature-dependent behaviour of soil particles (e.g., thermal expansion).

2 Purpose of this study

This testing program has prepared a constant volume swelling system that can be used with both distilled water and salinity water. The stainless-steel mold is highly resistant to chemical corrosion and holds specimens of compacted bentonite sand mixtures. Saline water has concentration variations of 1.2 %, 3.5 %, 6.0 %, and 8.0 %. The bentonite sand mixture sample in the steel mold is immersed in the solution. This process produces a chemical reaction involving montmorillonite as one of main minerals in bentonite. Moreover, to expand the investigation of the chemical reaction, carbon dioxide pressure is applied to the unsaturated and saturated specimens. This study investigates the thermal and chemical processes including effect of salinity and carbon dioxide. These two are serious problems in geotechnical environmental engineering.

In this study, the unconfined compressive strength of specimens subjected to THC performances was measured. All data presented an obvious alteration of the aforementioned effects. The measured unconfined compressive strength for unsaturated and saturated soils according to the process of these THC factors shows a reduction in shear resistance. The shear resistance was further reduced by the combined salinity and heating effects through THC coupling. The combined chemical and thermal loading therefore weakens the soil, which should be considered when assessing these impacts.

3 Influence of salinity

Saline water seepage is a major chemical loading on expansive soils. Once saturated with saline water, these soils show reduced swelling pressure and swelling deformation. The mechanical properties of softened or weakened soils must be characterised. The unsaturated specimens have a dry density of 1.600 Mg/m^3 and bentonite sand mixture ratio is 3:7. One specimen was submerged in distilled water under vacuum for one week, and the other specimen was submerged in

* Corresponding author: nishimura.tooyoshi@g.ashikaga.ac.jp

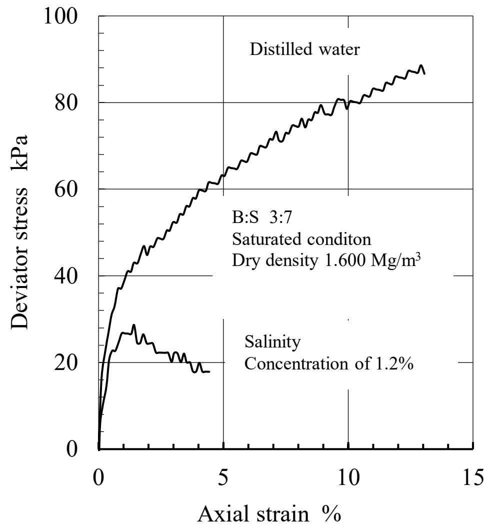

Figure 1. Stress-strain curve including salinity effects.

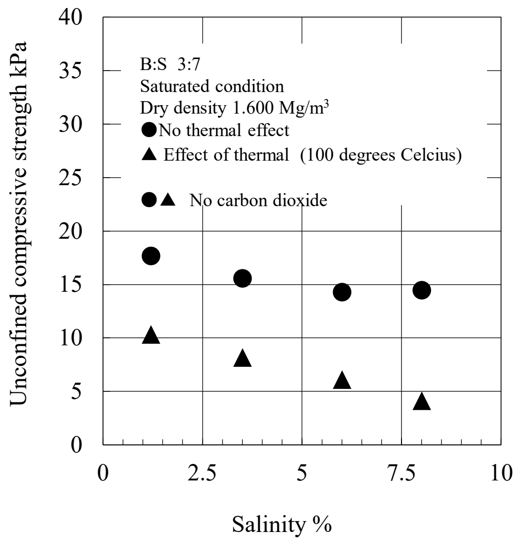

Figure 2. Effect of thermal and chemical coupled phenomena.

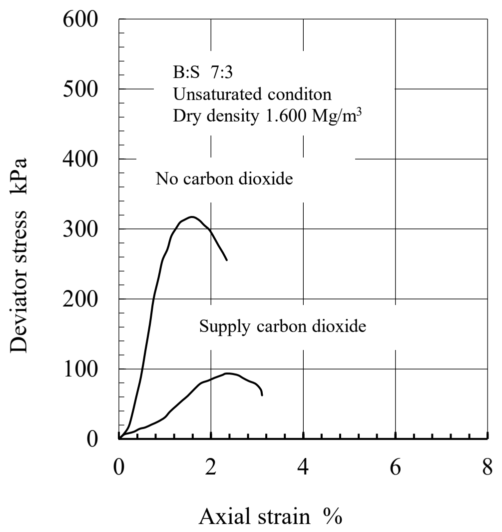

Figure 3. Reduction by carbon dioxide.

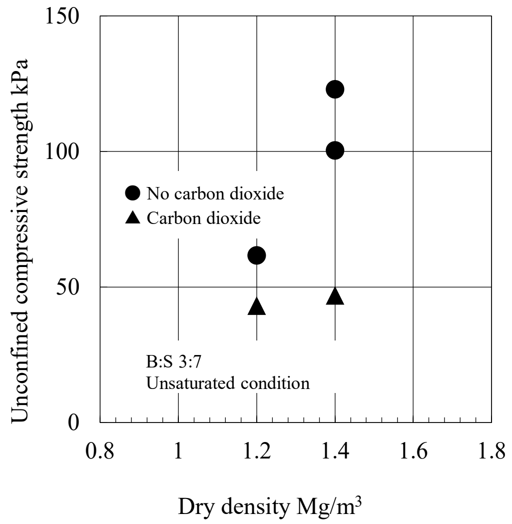

Figure 4. Effect of carbon dioxide (B:S 3:7).

water with concentration of 1.2% with a similar methodology saturation process in distilled water. Figure 1 shows the progressive increase in axial resistance for the distilled-water specimen, and 88.9 kPa was measured at the end of the test (i.e., the axial strain of 12.9%). No peak strength was reached. The salinity water reaction indicated a further reduction in shear resistance compared with distilled water seepage. The measured peak value is 28.7 kPa, and the axial strain is 1.2%. A reduction in stiffness was also observed. This change in mechanical properties shows the softening behaviour of the soil under saline loading.

4 Considering components for salinity

As shown in Figure 2, thermal effects are also discussed. Both the salinity reaction and thermal application were processed as follows: first, unsaturated specimens were saturated with saline water with various concentrations (i.e., 1.2%, 3.5%, 6.0%, and 8.0%) in the stainless-steel mold under constant volume. The specimens were divided into two groups. The first was tested under unconfined compression. The second was heated to 100 °C before testing. The saturated specimen with saline water remained constant in water content (i.e., no water leakage and no moisture loss) during heating at 100°C. The specimens were subjected to an unconfined compression test after the heating process for 24 h. The measured unconfined compressive strength showed a reduction according to the concentrations of saline water, as shown in Figure 2. Considering the range of water salinity, the strength decreased from 17.7 to 14.6 kPa. The influence of saline water is evident, although the magnitude of the strength reduction remains modest within this salinity range. Following the salinity reaction, the heating application at 100 °C is applied to all the saturated specimens. The reduction of unconfined compressive strengths is confirmed regardless of concentration in saline water. The amount of decrease in shear resistance due to heating appears to be large, depending on the salinity of the water. In the case of 8.0% concentration, the measured strength is 4.1 kPa, and the softening behaviour is clearly attributable to the coupled chemical–thermal loading (i.e., chemical reaction and heating effects).

5 Effect of carbon dioxide on unsaturated specimen

An unsaturated specimen with a dry density of 1.600 Mg/m^3 and bentonite sand mixture ratio of seventy-thirty was prepared. The measured stress–strain curve is shown in Figure 5; the unconfined compressive strength was 313.1 kPa. Subsequently, carbon dioxide pressure was applied for a period of two weeks, and the stress–strain curve was measured, as shown in Figure 3. A sharp difference is observed compared to the specimen without carbon dioxide application. The stiffness and unconfined compressive strength were significantly weakened.

6 Limitation on 3:7 and 5:5 unsaturated specimen with carbon dioxide

The reduction of unconfined compressive strength due to the application of carbon dioxide is considered, including changes in the dry density and bentonite sand mixture ratio. The unsaturated specimens showed a large reduction in shear resistance, as shown in Figure 4 and Figure 5. The unsaturated specimens without carbon dioxide pressure (i.e., no application of carbon dioxide) showed an increase in shear resistance with increasing the dry density. Subsequently, the unsaturated specimen subjected to carbon dioxide pressure has a dry density of 1.400 Mg/m^3 and showed higher resistance than shear resistance of the dry density of 1.200 Mg/m^3.

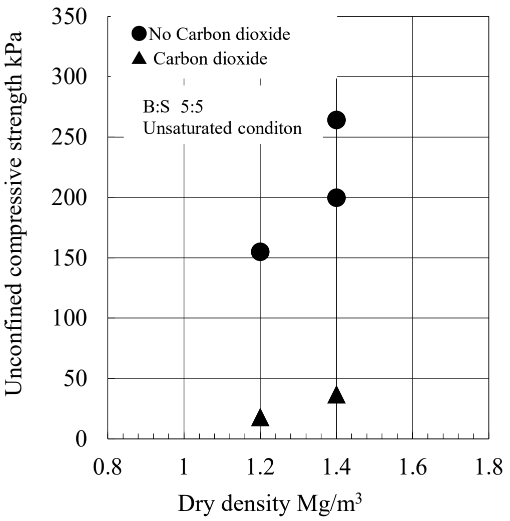

Figure 5. Effect of carbon dioxide (B:S 5:5).

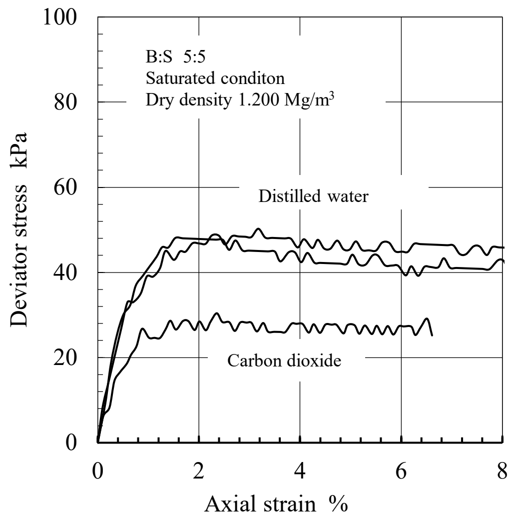

Figure 6. Effect of carbon dioxide for saturated specimen.

7 Influence of carbon dioxide for saturated specimen

A saturated specimen with a dry density of 1.200 Mg/m^3 and a bentonite sand mixture ratio of 50:50 was first saturated with distilled water, then subjected to carbon dioxide pressure inside the submerged chamber. The stress–strain curves are shown in Figure 6; the stiffness decreased substantially and a large reduction in shear resistance was observed.

8 Conclusions

This study addresses the following as a solution to Thermal Hydraulic Mechanical Chemical phenomena: unconfined compression test methodology, confirmation of reproducibility for soft soils, hydration performance of saturation process, chemical activity for liquid reaction using salinity water, and vapor application used in carbon dioxide pressure.

The specimen had no rubber membrane, and the cell pressure was applied under isotropic conditions. The two stress–strain curves have similar shapes and similar unconfined compressive strengths. The salinity water reaction indicated a further reduction in shear resistance compared with distilled water seepage. The change in mechanical properties shows the softening performance. The measured unconfined compressive strength decreased with increasing saline concentration. The decrease in shear resistance due to heating appears to be large. The application of carbon dioxide produced a large reduction in the unconfined compressive strength. The saturated specimen subjected to carbon dioxide pressure has a small stiffness and a large reduction in shear resistance.

References

1. C. García, T. Hernández, Biological and biochemical indicators in derelict soils subject to erosion. Soil Biol. Biochem. **29**, 171–177 (1997). https://doi.org/10.1016/S0038-0717(96)00294-5
2. E. Gartner, Industrially interesting approaches to “low-CO_2” cements. Cem. Concr. Res. **34**, 1489–1498 (2004). https://doi.org/10.1016/j.cemconres.2004.01.021
3. Z. Liu, Q. Peng, Q. Yang, H. Deng, Y. Xiao, D. Liu, Y. Yang, Bio-geotechnical reinforcement of purple soil slopes: the synergistic effects of xanthan gum biopolymer and planting density. Eng. Geol. **362**, 108540 (2026). https://doi.org/10.1016/j.enggeo.2025.108540
4. N. Raj, S. Selvakumar, K. Muthukkumaran, A review of bio-based stabilization methods for expansive soils. Biogeotechnics 100229 (2026). https://doi.org/10.1016/j.bgtech.2026.100229
5. H. Zhu, X. He, K. Wang, Y. Su, J. Wu, Interactions of vegetation succession, soil bio-chemical properties and microbial communities in a Karst ecosystem. Eur. J. Soil Biol. **51**, 1–7 (2012). https://doi.org/10.1016/j.ejsobi.2012.03.003
6. R. Bhatt, S. Arora, Impact of tillage on soil bio-chemical properties, water storage and environment. J. Soil Water Conserv. **14**, 278–282 (2015).
7. M. Bittelli, F. Ventura, G. Campbell, R. Snyder, F. Gallegati, P. Pisa, Coupling of heat, water vapor, and liquid water fluxes to compute evaporation in bare soils. J. Hydrol. **362**, 191–205 (2008).
8. D.A. De Vries, Thermal properties of soils, in Physics of Plant Environment (North-Holland Pub. Co., 1963), 210–235.
9. H. Gao, M. Shao, Effects of temperature changes on soil hydraulic properties. Soil Tillage Res. **153**, 145–154 (2015).