Research article

Changes in Soil Physical Properties Owing to Soil Reduction Treated with Electrokinetic Treatment

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Received 17 September 2023 Accepted 26 December 2023 (*****Corresponding Author)

Abstract Increasing soil water content due to soil reduction is generally confirmed in rice paddy soils after flood irrigation or in littoral sediments with high organic matter content. This could be caused by soil aggregates during the reduction process through biological and electrostatic phenomena. In the literature, changes in liquid and plastic limits owing to soil reduction treated with electrokinetic treatment (ET) have been reported; however, there was no report relating to changes in other soil physical properties, such as grain size distribution (GSD) and water-holding capacity (WHC). Thus, this study aimed to examine changes in soil physical properties caused by soil reduction treated with ET. Changes in GSD, hydraulic conductivity, and WHC were examined in laboratory experiments to understand soil aggregates due to soil reduction. During ET application, a decrease in electrical conductivity was observed, indicating the cohesion of ions (soil aggregate). This resulted in increases in the percentage of particles ranging from 0.075-0.212 mm, hydraulic conductivity, and WHC. However, particle dispersion occurred when the electrical current was high (10 mA), resulting in a significant decrease in hydraulic conductivity and WHC. Therefore, it can be said that soil aggregates can develop electrostatically. Thus, ET can be used for developing soil aggregate.

Keywords soil reduction, electrokinetic treatment, soil aggregate, grain size distribution, hydraulic conductivity, water-holding capacity

INTRODUCTION

In rice paddy fields, oxygen diffusion from air into the soil is suppressed after flood irrigation on the soil surface, causing soil reduction. Touch et al. (2021) experimentally examined soil redox potential (ORP) after making a water layer on paddy soils. They observed that soil reduction occurred in 45 days. Generally, the water content of paddy soil increases temporally during soil reduction. Ozaki et al. (2013) observed an increase in water content from 30% to 50% after flooding irrigation in winter. Moreover, an increase in water content due to soil reduction occurs in littoral sediments. Fukui et al. (2012) reported that the water content of sediments with high organic matter content is higher than that of sediments with low organic matter content. Hattori et al. (2018) reported an increase in water content with an increase in total organic carbon. Therefore, it can be said that organic matter influences the water content of sediments. However, the mechanisms behind the increasing water content owing to soil reduction or organic matter remain unclear.

It is believed that an increase in water content owing to soil reduction occurs through soil aggregate by biochemical and electrostatic mechanisms. Generally, the released substances during the decomposition of organic matter can act as binders in soil aggregate. With the proceeding of organic matter decomposition, and fungal hyphae development, water-stable aggregates increased and then decreased (Limura and Egawa, 1956). Many researchers have since focused on the correlation between soil organic matter and soil aggregate (Okolo et al., 2020; Mustafa et al., 2020).

Soil aggregate may also occur through electrostatic bonding. Liaki et al. (2010) investigated physicochemical effects on clay after ET application. They observed changes in water content owing to ET application and pointed out that ET application varied the zeta potential of clay particles, causing changes in share strength, liquid limit, and plastic limit of clayey soils. However, the effects of ET on other soil physical properties remain unknown.

OBJECTIVE

This study aims to examine changes in soil physical properties owing to soil reduction treated with ET. This can be done by inducing reduction reactions in upland soils with a constant flow of electrical current using a potentiostat (current fixation). Specifically, changes in grain size distribution (GSD), hydraulic conductivity, and water-holding capacity (WHC) are examined. In addition, changes in ion concentration present in soil pore water after the generation of electrical current are determined.

METHODOLOGY

Experimental Procedures and Operations

Figure 1 shows the experimental device, comprising a cylindrical bottle with an inner diameter and a height of 120 mm and 150 mm, respectively. First, the upland soil collected from the farmland was placed in the bottle until it reached a height of 20 mm from the bottom, and an electrode (anode) was placed on the soil layer. 30 mm of the soil layer was then placed on the electrode (Fig. 1a). Finally, tap water was poured over the soil layer. The bottle was then placed in a container (360 mm in width, 510 mm in length, and 300 mm in height) filled with tap water (Fig. 1b). In the container, an electrode (cathode) was submerged close to the water surface.

The electrode material was carbon cloth (News Company, PL200-E), which was heated at 500°C for 1 h before using it, as Nagatsu et al. (2014) suggested. The heated carbon cloth with a width of 10 cm and height of 10 cm was separated into fibers to form a brush-type electrode (Fig. 1c) used in the experiments.

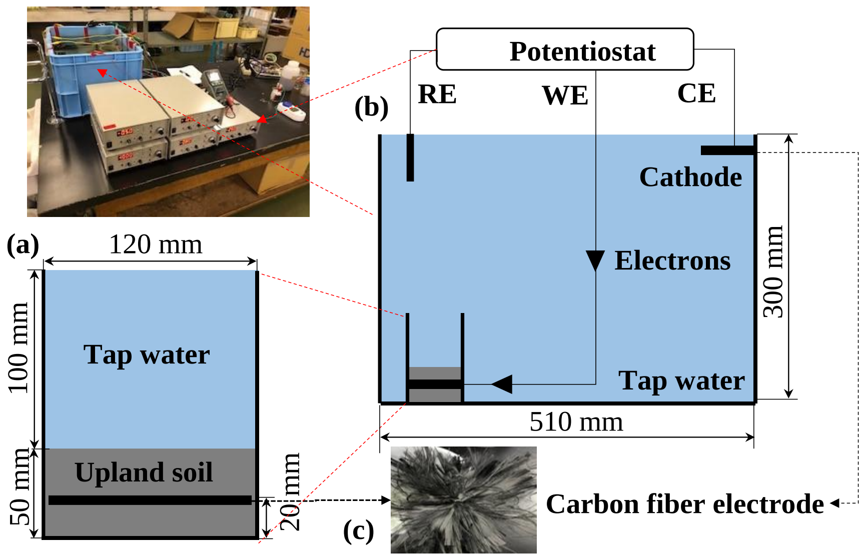


Fig. 1 Experimental devices and operations

To generate an electrical current, the anode, cathode, and reference electrode (Toyo Corp., W-RE-7A) were connected to a potentiostat (Hokuto, HA-151B) using the circuit shown in Fig. 1b. A potentiostat was used to maintain a constant electrical current of 4, 6, 8, and 10 mA. The current generation lasted for 7 days. As the treatment duration was less than 7 days, the effects of organic matter decomposition on soil aggregate are thought to be less significant.

Analyses

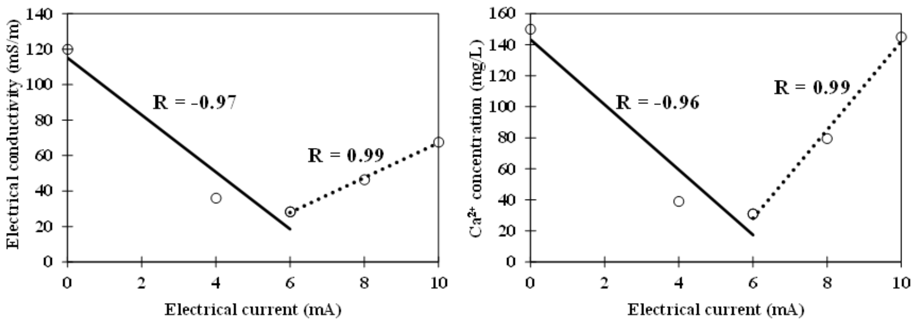
Soil sampling was conducted at the end of the experiments. Surface soil of 1 cm was removed, and the residue was centrifuged at 6000 rpm for 5 min (As One, CN-2060) to extract pore water. The electrical conductivity (EC) and calcium ion (Ca^{2+}) of extracted pore water were measured using an EC meter (Horiba, D-74) and a Ca^{2+} meter (Horiba, Ca-11), respectively.

Grain size distribution (GSD), hydraulic conductivity, and water holding capacity (WHC) were measured to examine changes in soil physical properties owing to soil reduction. GSD, hydraulic conductivity, and WHC were measured using the wet sieving method, the falling head permeability test, and the centrifugation method, respectively. In the falling head permeability test, the soil sample was placed in a 100 cm^3-sampler can with a soil surface area of approximately 20 cm^2 and a soil height of 0.4-1.2 cm. In the centrifugation method, the soil sample was centrifuged at 500 rpm (pF = 2) and 3900 rpm (pF = 3.8).

RESULTS AND DISCUSSION

Changes in Ion Conditions in Soil Pore Water Owing to Soil Reduction

Figure 2 shows changes in EC and Ca^{2+} concentration in soil pore water at different electrical currents. EC is an index that indicates the total ion concentration. Generally, changes in ion concentration by cohesion or dispersion cause a variation in EC. For example, from Fig. 2a, EC decreased from 120 mS/m to 28 mS/m with an increase in electrical current from 0 mA to 6 mA and increased from 28 mS/m to 68 mS/m with an increase in electrical current from 6 mA to 10 mA.



(a) Electrical conductivity (EC) *(b) Ca^{2+} concentration*

Fig. 2 Electrical conductivity and Ca^{2+} concentration at different electrical currents

In other words, decreases in ion concentration occurred when the electrical current increased until 6 mA, and the release of ions occurred when the current was higher than 6 mA. This can be confirmed in Fig. 2b, wherein Ca^{2+} concentration decreased from 150 mg/L to 31 mg/L when the electrical current increased from 0 mA to 6 mA. However, when the electrical current was higher than 6 mA, Ca^{2+} concentration increased from 31 mg/L to 145 mg/L. These results suggest that ion cohesion occurs in soils with an increase in electrical current from 0 mA to 6 mA. Interestingly, ion dispersion occurs in soils with an increase in electrical current from 6 mA to 10 mA. Furthermore, it was observed that ion cohesion or dispersion strongly correlates with electrical current, and the correlation coefficient was higher than 0.95 (Fig. 2). It is thought that this cohesion or dispersion induces soil aggregates, resulting in changes in soil physical properties.

Changes in Grain Size Distribution Owing to Soil Reduction

Based on the results of the sieve analysis, the residual rates on the sieve range of 0.075-0.212 mm, 0.212-0.850 mm, and 0.850-2 mm were determined, and Fig. 3 shows their relationship with the electrical current. In Fig. 3, the correlation coefficients were 0.22 and 0.41 for the particle size range of 0.85-2 mm and 0.212-0.850 mm, respectively. This suggests that soil reduction has less effect on particles larger than 0.212 mm.

Interestingly, the residual rate of the particle size range of 0.075-0.212 mm increased with an increase in electrical current, with a correlation coefficient of 0.61. Thus, it can be said that soil reduction causes the cohesion of soil particles less than 0.075 mm, contributing to the increase in residual rate. Liaki et al. (2010) and Wang et al. (2022) reported that generating electrical current in the soil causes changes in the zeta potential of soil particles, leading to cohesion or dispersion of the particles responding to an increase or decrease in zeta potential.

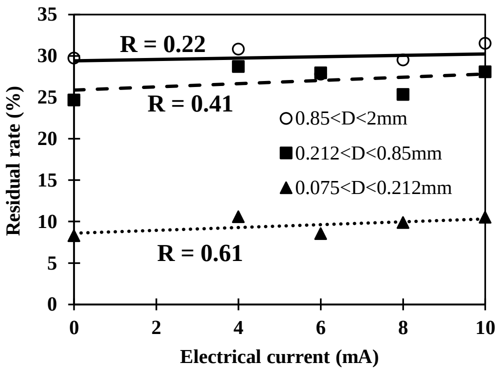
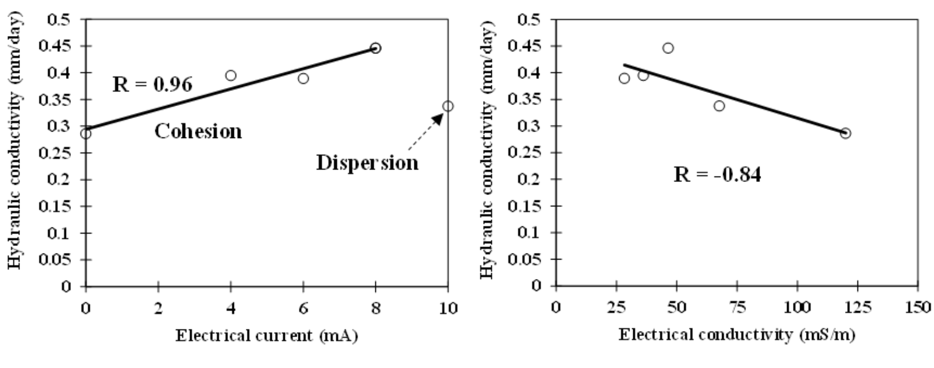


Fig. 3 Particle cohesion due to soil reduction

Changes in Hydraulic Conductivity Owing to Soil Reduction

Figure 4 shows the hydraulic conductivity at different electrical currents and its relationship with EC. The hydraulic conductivity increased from 0.29 to 0.45 mm/day when the current increased from 0 mA to 8 mA (Fig. 4a). Based on Fig. 2, the cohesion of particles occurred in the electrical current range of 0-6 mA. This cohesion induced soil aggregates, leading to an increase in hydraulic conductivity.



(a) Hydraulic conductivity (b) Correlation of hydraulic conductivity with EC

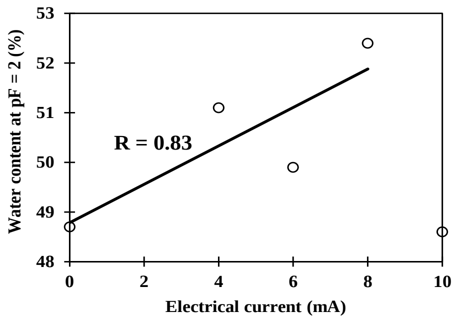
Fig. 4 Hydraulic conductivity at different electrical currents and its relationship with EC

Furthermore, the dispersion of particles occurred in the electrical current range of 6-10 mA. However, there was no decrease in hydraulic conductivity when the current was 8 mA, while there was a decrease when the current was 10 mA (Fig. 4a). This indicates that cohesion and dispersion of particles influence the hydraulic conductivity of soils, and a high rate of dispersion causes large decreases in hydraulic conductivity. It was also observed that hydraulic conductivity had a strong correlation (R = −0.84) with EC, and a larger hydraulic conductivity with a lower EC (cohesion state).

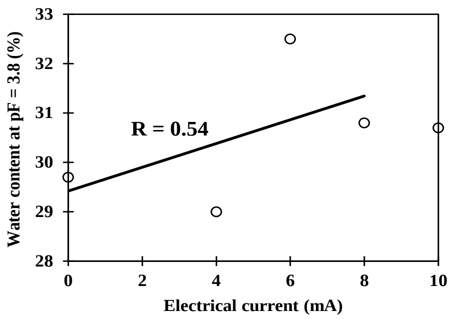
Changes in Water-Holding Capacity Owing to Soil Reduction

Generally, soil aggregates influence not only hydraulic conductivity but also the WHC of soils. Figure 5 shows the water content at pF 2 and 3.8. A similar trend was observed with the variation in hydraulic conductivity. The water content at pF 2 increased with an increase in electrical current from 0 mA to 8 mA, and a strong correlation (R = 0.83) was observed (Fig. 5a). An increase in the water content at pF 3.8 was also observed (Fig. 5b); however, the correlation was less significant (R = 0.54). In addition, a large decrease in water content was observed when the current was 10 mA (Fig. 5a). From Fig. 5a, it can also be said that the cohesion of soil particles induces soil aggregates, which increases WHC; however, high rates of particle dispersion decrease WHC.

Commonly, there are three types of water in soil: adhesion (the water on the surface of soil particles), cohesion (the water attached to adhesion water), and gravitational (the water that flows with gravitational force). The water content at pF larger than 1.8 refers to the amounts of adhesion and cohesion water. From these results, because a strong correlation between the electrical current and the water content at pF 2 was observed, it is thought that only cohesion water is influenced by electrical current generation (soil reduction).



(a) Water content at pF 2



(b) Water content at pF 3.8

Fig. 5 Hydraulic conductivity at different electrical currents and its relationship with EC

CONCLUSIONS

Laboratory experiments were conducted to examine the electrostatic effects of soil reduction on the physical properties of soil. Specifically, we examined changes in GSD, hydraulic conductivity, and WHC after introducing an electrical current into the soil (i.e., soil reduction caused by ET). When the electrical current was increased from 0 mA to 10 mA, EC and Ca^{2+} concentrations decreased when the current was less than 6 mA and increased when the current was higher than 6 mA. This suggests that the cohesion of particles occurs in soils due to soil reduction; however, a high current (10 mA) can lead to the dispersion of soil particles. From GSD, the residual rate of the particle size range of 0.075-0.212 mm increased when the current increased, indicating that soil reduction causes soil aggregates. Furthermore, the hydraulic conductivity had a strong correlation (R = −0.84) with EC, indicating that cohesion or dispersion influences the hydraulic conductivity of soils. This study also confirmed that hydraulic conductivity and WHC increased when the cohesion of soil particles occurred. Therefore, it can be concluded that soil aggregates can form electrostatically during soil reduction. In other words, ET can be used to develop soil aggregates and change the physical properties of soils.

ACKNOWLEDGMENTS

The authors gratefully acknowledge partial funding from the Tokyo University of Agriculture: FY2021 Grant-in-Aid for Sustainable Agriculture Research Projects. The authors would like to thank the students of the Rural Environmental Engineering Laboratory, Tokyo University of Agriculture, for their efforts in collecting data.

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