沙漠研究 **24**-1, 81-84 (2014)
Journal of Arid Land Studies

－ DT11 Refereed Paper －

Evaluation of Salt Transport in the Amelioration of Salt-Affected Soil in China by Using Low-Quality Coal Bio-Briquette Ash

Yuji SAKAI*[1], Hitomi SETO[1] and Hidetoshi NAGAMOTO[1]

Abstract: In countries with arid and semiarid regions, a decrease in agricultural production due to excessive salts in the soil is a very serious problem. Recently, the need for development of new, clean coal-refining technologies has risen in China. In this study, we ameliorated salt-affected soil by using coal bio-briquette ash, and the positive effects of this amelioration have been confirmed. In addition, we investigated the effect of salts leaching into coal bio-briquette ash by using a soil column equipped with tensiometers and 4-electrode sensors. Ashes from 2 coal bio-briquettes made from low-quality coal (sulfur content = 2.1% and 4.1%), biomass (corn stem), and a desulfurizer ($Ca(OH)_2$) were added to salt-affected soil. Consequently, initial sodium (Na) leaching was confirmed from the results of the leachate electroconductivity (EC) and Na content of the leachate at a 3.0wt% application rate. The effect of soil amelioration by using coal bio-briquette ash originating from high-sulfur coal was more effective than that from low-sulfur coal. Our research also indicates that ash has the capability of ameliorating high-EC and high exchangeable sodium percentage soils. Finally, we predicted the necessary water volume for Na leaching in all fields by using the experimental results from the soil column and the meteorological data from all cities. Consequently, we could estimate the quantity of irrigation water necessary in all cities. These results indicated the effectiveness of using low-quality coal bio-briquette ash as an amendment to salt-affected soil, and its use in predicting the reclamation time and necessary volume of water for soil amelioration.

Key Words: Coal bio-briquette, Hydraulic conductivity, Salt-affected soil, Salt transport, Soil amelioration

1. Introduction

Salt-affected soils occur in more than 100 countries worldwide, with variations in the extent of affected soil and nature and properties of the soil (Rengasamy, 2006). The decrease in agricultural production due to excessive salts in the soil is a very serious problem, because insoluble salts that have accumulated in the soil obstruct the growth of vegetation because of the osmotic pressure that they exert. Moreover, the accumulation of monovalent cations (mainly sodium, Na^+) causes deterioration of the soil's physical properties from the dispersion and swelling of clay, which makes it difficult for plants to grow. These processes adversely affect water penetration, infiltration speed, and moisture transport properties of the soil. Therefore, leaching unwanted chemicals from the soil by using large amounts of water is required to improve such salt-affected soils.

The use of chemical amendments is an effective method to reclaim salt-affected soils. Amelioration of salt-affected soil involves the replacement of exchangeable Na with calcium (Ca) supplied by the presence or addition of gypsum, soil lime, or both (Oster and Frenkel, 1980). Reclamation can be achieved by leaching with chemical amendments added to the soil or irrigation water (Keren and Miyamoto, 1990). Soil salinity can be directly measured using buried porous electrical conductivity (EC) sensors, 4-electrode probe systems, electromagnetic induction sensors, or time domain reflectometry systems (Rhoades and Oster, 1986; Rhoades, 1992). In particular, a 4-electrode probe has been shown as suitable for observing the salt concentration in a column with water flow (Inoue *et al*., 2000).

On the other hand, in China, air pollution is also a serious environmental problem. Recently, desulfurization equipment was installed at large facilities such as coal-fired power plants. However, low-quality coal containing high percentages of sulfur and ash are used for cooking and heating in rural households in China; therefore, indoor pollution from coal combustion in rural areas is a critical problem, and there are many concerns about damage to health. Hence, we used coal bio-briquettes that also have merits because of their desulfurization ability and can be made using low-quality coal and biomass in China. Moreover, Sakai *et al*. used the combustion ash of coal bio-briquettes as salt-affected soil amendments in China and effective reclamation results have been confirmed (Sakai *et al*., 2011).

In this study, our objective was to investigate the effect of Na leaching and the water volume necessary for Na leaching

* Corresponding Author: sakai@cc.kogakuin.ac.jp
2665-1 Nakano-machi, Hachioji-shi, Tokyo 192-0015, Japan
1) Department of Environmental and Energy Chemistry, Kogakuin University, Japan

(Received, September 14th, 2013; Accepted, February 10th, 2014)

Table 1. Soil chemical properties, hydraulic conductivity (K_W), and soil texture of 4 tested soils.

	pH [-]	EC[dS m^{-1}]	ESP*[%]	K_w**[cms^{-1}]	ST***
Soil 1	10.5	0.8	25.0	6.6×10^{-8}	SCL
Soil 2	10.1	0.6	20.4	1.9×10^{-6}	LS
Soil 3	9.3	2.1	35.0	2.6×10^{-6}	SCL

*ESP: exchangeable sodium percentage, **Kw: Saturated hydraulic conductivity, ***ST: Soil Texture

Table 2. Chemical properties of soil amendments.

	pH[-]	EC [dS m^{-1}]	ex. Ca**** [mmoldm^{-3}]
BB 1*	8.5	2.3	14.7
BB 2**	10.9	2.4	27.4
$CaSO_4$	7.4	2.1	152
$CaSO_4 + Ca(OH)_2$***	12.7	8.9	277

*BB 1: Combustion ash from coal bio-briquette (S content in coal = 2.1%) **BB 2: Combustion ash from coal bio-briquette (S content in coal = 4.1%), ***: $CaSO_4$:$Ca(OH)_2$ = 1:1 (weight ratio), ****ex. Ca: exchangeable calcium concentration

by using coal bio-briquette ash made from low-quality coal as an amendment for salt-affected soil. In addition, we predicted the necessary volume of irrigation water for field tests from both the experimental results and meteorological data from each test site.

2. Materials and Methods

2.1. Soil properties and soil amendments

Three soils (Soil 1, Soil 2, and Soil 3) were used for the column infiltration experiment. Soil 1, Soil 2 and Soil 3 were sampled in Shenyang, Datong and Yinchuan, China, respectively. Chemical properties such as soil pH, EC, and exchangeable sodium percentage (ESP) are provided in **Table 1**. All soils are characterized by a high pH and high ESP. In particular, EC and ESP in Soil 3 were higher than that in other soils. Saturated hydraulic conductivity (K_W) of Soil 1 was lower than that in other soils. Two types of ash from coal bio-briquettes made with low-quality coal with sulfur (S) contents of 2.1% and 4.1% were used for soil amendment. Ashes were labeled BB 1 (S = 2.1%) and BB 2 (S = 4.1%). For reference, the $CaSO_4$ and $CaSO_4 + Ca(OH)_2$ (weight ratio = 1:1) properties are provided in **Table 2**. The pH, EC and ion concentration of a 50-mL solution mixed with 10 g soil were measured using a pH meter and an EC meter (F-55, Horiba) and an ICP-AES (SPS3500UV, SII), respectively. The chemical properties of the soil amendments were measured in solution (soil: water = 1:10 (weight ratio)). The pH in BB 2 and $CaSO_4 + Ca(OH)_2$ was higher than that in BB 1 and $CaSO_4$. EC in $CaSO_4 + Ca(OH)_2$ was the highest in all soil amendments. The concentration of exchangeable calcium (Ca) in BB ash was lower than that in Ca compounds.

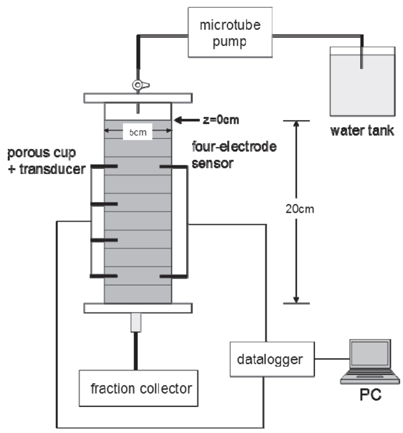

Fig. 1. Schematic illustration of the experimental column setup.

2.2. Column Infiltration Test

Soil samples < 2 mm were mixed uniformly with BB ashes at application rates of 3.0 wt% at a bulk density of 1.53 g cm^{-3}. An acrylic ring with an outer diameter of 60 mm, inner diameter of 50 mm, and height of 20 mm was filled to 20 cm. Degassed water was poured onto the top of the column at a rate of $1.0 \times 10^{-3} – 2.0 \times 10^{-3}$ cm^3 s^{-1} by using a peristaltic pump. Tensiometers and 4-electrode sensors (Inoue *et al*., 2000) were inserted into the column at depths of 5, 9, 13 and 17 cm, and at 5 and 17 cm (where soil surface z = 0 cm), respectively. In our research, we used a 4-electrode sensor as an indicator of total salt concentration in the soil column to observe the runoff rate of salts. Tensiometers were equipped with a transducer to measure the pressure (cmH_2O) of the soil in the experimental column. Transducers (TD 1 [z = 5 cm], TD 2 [z = 9 cm], TD 3 [z = 13 cm] and TD 4 [z = 17 cm]) connected to 4 tensiometers and two 4-electrode sensors (FES; FES 1 [z = 5 cm] and FES 2 [z = 17 cm]), were connected to a data logger (CR10X, Campbell Scientific, Inc.) using a PC (**Fig. 1**). The measurements were controlled in the program by using the application software (PC208W, Campbell Scientific, Inc.). Moreover, to examine the soil solution that seeped from the lower part of the experimental column, we collected the infiltration solution at constant time intervals using a fraction collector. The water volume was measured at each time interval. The ion concentrations (Na^+, Ca^{2+}, magnesium (Mg^{2+}), potassium (K^+) and chlorine (Cl^-)) in the effluent solution were quantified using ICP-AES. The soil pH and EC of each solution were also measured. These experiments were performed at 25°C.

3. Results and Discussion

We examined the effect of Na leaching using BB 1 and BB 2 in Soil 2. The effect of Na and electrolyte concentrations in relation to Kc and infiltration were discussed. Swelling and

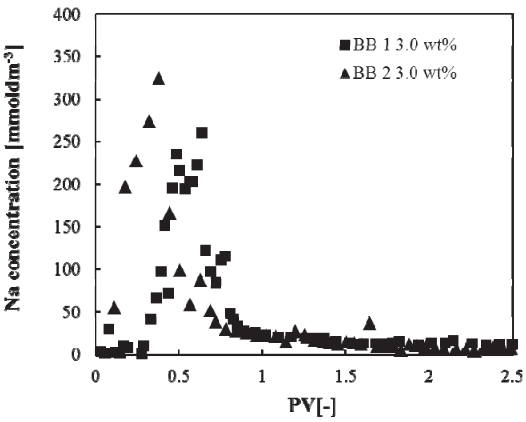

Fig. 2. Change in Na concentration of leachate at the application rate of 3.0 wt% (BB 1, BB 2).

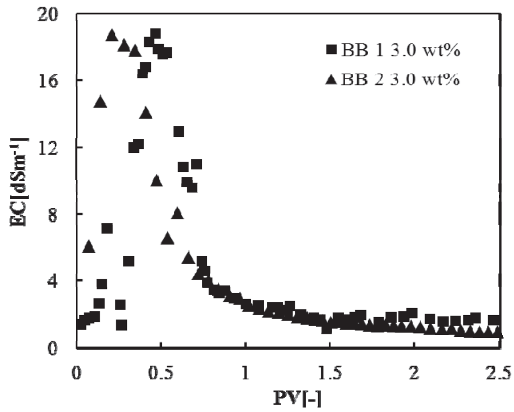

Fig. 3. Change in electrical conductivity (EC) of leachate at the application rate of 3.0 wt% (BB 1 and BB 2).

dispersion are the primary processes responsible for degradation of the physical properties of soil in the presence of Na. The Na concentration in effluent after infiltration into the column decreased by about 1 PV (pore volume) (**Fig. 2**). The behavior of leachate EC in the BB 1 and BB 2 applications was similar to Na concentration in BB 1 and BB 2, respectively (**Fig. 3**). The necessary water volume under 4 dS m^{-1} was 0.77 PV (0.116 dm^3) in BB 1 and 0.78 PV (0.107 dm^3) in BB 2 (Fig. 3).

In a previous study in Soil 1, that was 0.90 PV (0.142 dm^3) in 0.5 wt% application rate of $CaSO_4$ (Sakai *et al.*, 2009). This result indicates that the necessary water volume for soil amelioration in coal bio-briquette ash is smaller than that in gypsum. The K_c in the soil column after 1 PV in BB 1 and BB 2 was approximately 10^{-4} cm s^{-1} and 10^{-6} cm s^{-1}, respectively (**Fig. 4**). The difference between the 2 hydraulic conductivities is a result of the difference of exchangeable Ca concentration (Table 2).

Next, BB 2 was added to Soil 1, Soil 2 and Soil 3 at the application rate of 3.0 wt%. Na concentration and EC in the leachate of all soils increased at the beginning of the leaching process and then drastically decreased (**Figs. 5** and **6**). Most

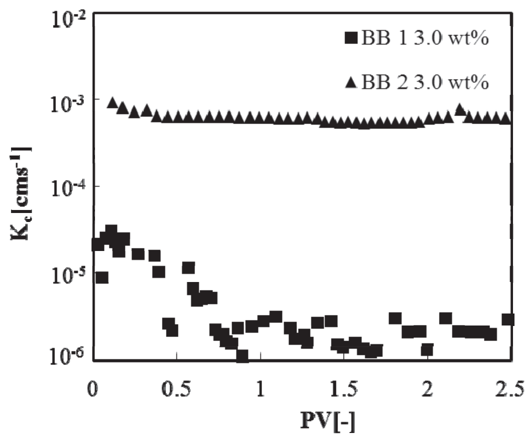

Fig. 4. Change in hydraulic conductivity (K_c) in the soil column at the application rate of 3.0 wt% (BB 1, BB 2).

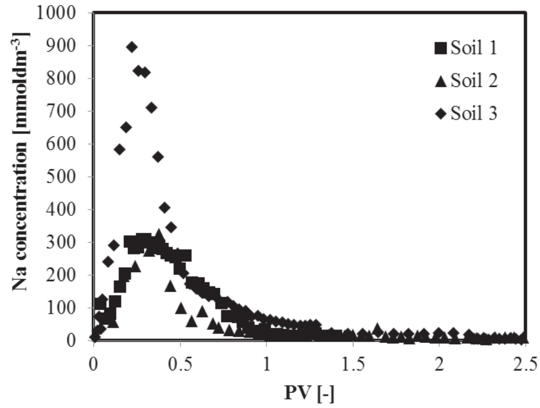

Fig. 5. Change in sodium (Na) concentration of leachate at 3.0 wt% application rate of BB 2 (Soils 1, 2 and 3).

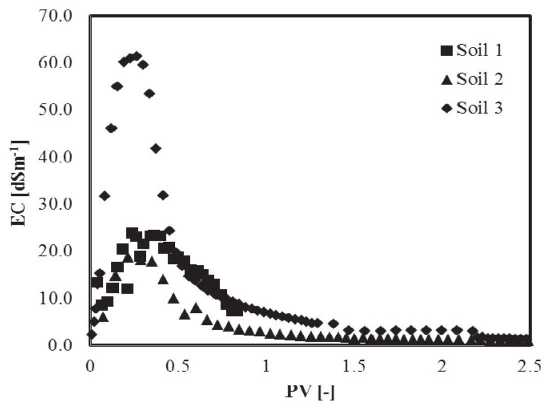

Fig. 6. Change in electrical conductivity (EC) of leachate at 3.0 wt% application rate of BB 2 (Soils 1, 2 and 3).

of the salts, mainly Na, were leached in 1 PV; therefore, the water volume for salt leaching in soil was nearly the same, and the total time for soil reclamation depended on the water penetration speed. The order of K_c in the soil column was almost the same as that in the original soil (**Fig. 7** and Table 1). This addition of divalent cations to the soil solution can reduce clay dispersion and increase K_c in the soil profile (Keren and Miyamoto, 1990); therefore, Ca ion originating from coal bio-briquette ash was effective for reclamation of K_c in soil.

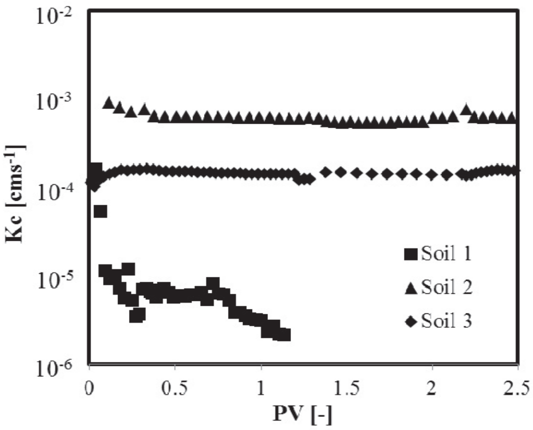

Fig. 7. Change in hydraulic conductivity (Kc) in the soil column at 3.0 wt% application rate of BB 2 (Soils 1, 2 and 3).

Table 3. Simulated necessary irrigation water volume in all sites in China.

	Water quantity for Na leaching in column experiment (Q) [dm^3]	Quantity of infiltration water to soil (I) [dm^3]	Necessary irrigation water volume (Q-I) [dm^3]
Soil 1	0.2498	0.1334	0.1164
Soil 2	0.2384	0.2016	0.0368
Soil 3	0.3479	0.1027	0.2452

We predicted the completion time for salt leaching in the test field by using the results obtained from the column experiment, water balance equation, evapotranspiration equations, and meteorological data (Sakai *et al*., 2009). In this study, the effect of coal bio-briquette ash was compared with that of desulfurization gypsum (Sakai *et al*., 2009). This simulation method is the same concept; however, both average temperature and precipitation during the corn-growing season (from April to October) in 3 cities was introduced to the water-balance equation, and the quantity of irrigation water and total shortwave radiation was assumed to be the same value in the 3 cities. Consequently, the necessary water quantities for Na leaching in the soil column experiment (Q) were 0.2498 dm^3 in Soil 1, 0.2384 dm^3 in Soil 2 and 0.3479 dm^3 in Soil 3 (**Table 3**). Considering the average temperature and precipitation in each city, the quantity of infiltration water to soil (I) was 0.1334 dm^3 in Soil 1, 0.2016 dm^3 in Soil 2 and 0.1027 dm^3 in Soil 3 (Table 3); therefore, their water quantity was insufficient for leaching nearly all Na in the soil. Since the average irrigation water quantity in China is approximately 0.1472 dm^3 (Tian *et al*., 2003), the necessary irrigation water volume for Soil 1 and Soil 2 was within this average volume; however, in Soil 3, the irrigation water volume had to be increased.

4. Conclusion

Combustion ashes from coal bio-briquette made using low-quality, high-sulfur coal was effective for Na leaching in salt-affected soil amelioration. Coal bio-briquette ash containing a large amount of exchangeable Ca is highly capable of K_c reclamation and salt leaching. By using the column infiltration test, the necessary water volume for salt leaching was found to be nearly constant and the period of reclamation depended on the K_c. Thus, by using our simulation model, the necessary irrigation water volume could be calculated.

Acknowledgement

We express our appreciation to Prof. Changhe Chen (Tsinghua University) and Prof. Chang Wang (Tianjin University of Science & Technology) for their assistance in this experiment and investigation. This study was supported by the Kurita Water and Environment Foundation (KWEF).

References

Inoue M., Simunek J., Shiozawa S., Hopmans J.W. (2000): Simultaneous estimation of soil hydraulic and solute transport parameters from transient infiltration experiments. *Adv. Water Resour.*, **23**: 677-688.

Keren R., Miyamoto S. (1990): Reclamation of saline and, sodic and boron-affected soils. *In* Tanji K.K. ed., *Agricultural salinity assessment and management.* American Society of Civil Engineering, New York. 410-431.

Oster J.D., Frenkel H. (1980): The Chemistry of the Reclamation of Sodic Soil with Gypsum and Lime. *Soil Sci. Soc. Am. J.*, **44**: 41-45.

Rengasamy P. (2006): World salinization with emphasis on Australia. *J. Exp. Bot.*, **57**: 1017-1023.

Rhoades J.D., Oster J.D. (1986): Solute content. *In* Klute A. ed., *Methods of soil analysis part 1. 2nd ed*. SSSA, Madison, WI, 985-994.

Rhoades J.D. (1992): Instrumental field methods of salinity appraisal. *In* Topp G.C., Reynolds W.D., Green R.E. eds., *Advances in measurement of soil physical properties: bringing theory into practice. SSSA Special Pub. No. 30.* 231-248.

Sakai Y., Shitara S., Sadakata M. (2009): Salts Transport in Alkali Soil Reclamation by Gypsum and Prediction of Na Leaching in Field in China, *Journal of Water and Environment Technology*, **7**: 121-133.

Sakai Y., Murata H., Ebato C., Liu D., Nagamoto H., Sadakata M. (2011): Salt-affected soil amelioration using coal bio-briquette ash in China. *Proceeding of 241st ACS National Meeting*.

Tian Y., Li F., Liu P. (2003): Economic analysis of rainwater harvesting and irrigation methods, with an example from China. *Agr. Water Manage.*, **60**: 217-226.