

# Impacts of soil slaking and drying on release and retention of cations during desalinization from saline soil

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**Abstract:** The mechanism of soil slaking is the breaking of soil aggregates by entry of water which is accompanied by salt releasing process when the soil contains salt. The objective of this paper is to describe the impacts of soil drying and slaking on cations release to outer solution and shift of cations during desalinization under different initial water contents (IWC). A slaking test on natural and air-dried soils was carried out for evaluating the effect of slaking in different IWC (60, 50, 40, 30, 20 and 10 % by weight). After 24 hours immersion in water, Na was predominantly released in every case both of the natural and air-dried soils. At the water content of 30 % that is around optimum slaking water content, maximum Na was released and at the water content of minimum slaking rate the release of Na was lowest. However, too dry condition (10 % water content) did not contribute to release Na more. On the other hand, we did not find any special relationship between the IWC and release of other cations like Ca, Mg and K in outer solution. Most of the  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  stay in exchange site (60 to 80 %) in soil and little amounts of them came out in outer solution. Water-soluble cations in slaked and unslaked soils followed the order of  $\text{Na} \gg \text{K} > \text{Mg} > \text{Ca}$  whereas, the amount of exchangeable state cations followed  $\text{Na}^+ > \text{Mg}^{2+} > \text{Ca}^{2+} > \text{K}^+$ . As a whole, the proportion of Na released in outer solution of natural soil was greater than that of air-dried soils. The results indicate that the water content for optimum slaking and the slower slaking rate is more efficient for desalinizing of Na from the saline soil.

**Key Words :** soil slaking, soil water content, cations release, desalinization, exchangeable state

## 1. Introduction

Salinity within irrigated soils clearly limits productivity in vast areas of Japan and other parts of the world. Soil degradation caused by salinization and sodification is of great concern in the modern world because it reduces potential agricultural lands (Tanji, 1990; Sadiq et al., 2007).

Although salinity has adversely affected agriculture for thousands of years, the recognition that salt-affected land

can be used for agriculture is relatively recent. Interest in the use of saline land resources has escalated over the last 20 years, with a renewed focus on saline agriculture in a range of countries including Pakistan (Qureshi and Barrett-Lennard, 1998), Australia (Barrett-Lennard and Malcolm, 1995; Marcar et al., 1995; Bennetta et al., 2009), the Middle East and North Africa (ICBA, 2006). In humid areas like Japan, residual salt in polder soil and salt in ground water affected by sea water intrusion can cause salt accumulation and damage crop growth, in particular, on polders and low land areas along sea coasts.

In reclaiming those saline soils to find out the effective (an efficient and low cost) method is required. Soil slaking is the process of soil aggregates collapse when they are rewetted after drying. The slaking has long been studied from the stand point of stability of aggregates. However, it has not been studied from that of salt removal. Drying followed by rewetting and slaking is commonly found in a natural soil processes. During the process, salt in the soil moves and accumulates to inner and outer surface of soil blocks and released to outer solution. But the details of cation shifting are not well understood. Akae et al. (2003) had also reported that slaking is the salt releasing process and salt concentration was decreased from shallow layer to the deeper layer accompanied with land drying processes. Note that breakdown of soil aggregates results in collapse of pores, which reduces infiltration rate, leads to runoff and erosion, and may, subsequently cause soil degradation.

Our previous research successfully identified the optimum water content for slaking of a studied soil and salt release from soil blocks (Shamim and Akae, 2010). The optimum soil slaking occurred when the gravimetric water content was around 30 % equivalent to pF 4.25 (1800 kPa). It is close to the shrinkage limit (31.8 %) which is the critical water content for air-entry of this soil. The results revealed that the maximum salt is released at the soil water content of maximum slaking. In addition, the amount of salt released into equilibrium water after 24 hours immersion was proportional to the fraction of slaked soils (slaking rate). Here, we hypothesize that desalinization may be enhanced by simply putting the soil at the proper soil water content by land drying practice or by rewetting.

In this study, the amount of Na in the outer solution

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**Table 1** Fundamental properties of Kojima Bay Polder (paddy field; depth: 50 – 70 cm).

Properties	Unit	
Texture	Silty clay	
Clay	38.2	%
Silt	50.4	%
Sand	11.4	%
Soil pH	7.5	
(Soil : Water = 1 : 2.5)		
Hardness	3.83	mm
Particle density	2.51	$\text{g cm}^{-3}$
Plastic limit	39.5	%
Liquid limit	72.9	%
Electrical Conductivity	2.92	$\text{dS m}^{-1}$
(Soil : Water = 1 : 2.5)		
Exchangeable ions (Bolt et al., 1976)		
Sodium	19.6	$\text{c mol}_c \text{ kg}^{-1}$
Potassium	3.26	$\text{c mol}_c \text{ kg}^{-1}$
Calcium	7.72	$\text{c mol}_c \text{ kg}^{-1}$
Magnesium	10.7	$\text{c mol}_c \text{ kg}^{-1}$
Water-soluble ions (Soil : Water= 1 : 5 by weight)		
Sodium	8.45	$\text{c mol}_c \text{ kg}^{-1}$
Potassium	0.74	$\text{c mol}_c \text{ kg}^{-1}$
Calcium	0.28	$\text{c mol}_c \text{ kg}^{-1}$
Magnesium	1.26	$\text{c mol}_c \text{ kg}^{-1}$

surrounding the slaked soil blocks was mainly discussed, which is an exact measure of Na exclusion from the soil block. In addition, sites and states (exchangeable sites and soluble salts) of cations in soil were examined.

## 2. Material and methods

### 2.1 Sample collection and analysis method

The soil was collected from the depth of 50 to 70 cm (salinized layer) of Kojima Bay Polder (paddy field:  $34^{\circ}32'15.1''$  N and  $133^{\circ}55'37.0''$  E), located in Okayama prefecture in western Japan. The soil is classified to Ochric Gley Sols and the land use is rice cultivation. The clay minerals of the soil are composed of mainly halloysite-illite intermediate, nontronite and montmorillonite accompanied with quartz, feldspars, chlorite and free sesquioxides (Kawaguchi et al., 1957). The disturbed soil samples were air-dried and mixed with distilled water at the ratio of 1 : 5 by weight. Then the supernatant water was taken and  $\text{EC}_{1:5}$  were measured using a portable electrical conductivity meter (B-173; Horiba Ltd.). The soil pH was measured in a 1 : 2.5 (Soil : Water by weight) suspension using a portable pH meter (B-212; Horiba Ltd.).

Soluble cation concentrations were measured using an atomic absorption spectrophotometer (AAS; Z 5300; Hitachi Ltd.) in the supernatant water after centrifuging the natural soil. Insoluble salts and exchangeable cations were extracted using ammonium acetate. The 1.0 g of the

disturbed air-dried soil was mixed with 200 ml solution (0.0114 M  $\text{SnCl}_2 \cdot 6\text{H}_2\text{O}$  and 1 N  $\text{CH}_3\text{COONH}_4$ ) then the mixture was shaken for 1.5 hours. After settling and centrifuging, the cations in the supernatant were analyzed by the AAS. Finally, we subtracted the amount of free ions from that of the total ions to obtain true amount of exchangeable cations (Bolt et al., 1976). Fundamental physical properties of soils; particle size distribution, soil density, hardness, Atterberg Limits were measured by the standard methods of the Japanese Geotechnical Society (The Japanese Geotechnical Society, 2000).

### 2.2 Fundamental properties of the studied soil

Fundamental properties of the studied soils are given in Table 1. The studied soil showed a silty clay texture (clay 38.2, silt 50.4 and sand 11.4 %); the pH and  $\text{EC}_{1:5}$  were 7.5 and  $2.92 \text{ dS m}^{-1}$ , respectively. The soil has relatively higher liquid limit of 72.9 %. Both the water-soluble ( $8.45 \text{ c mol}_c \text{ kg}^{-1}$ ) and exchangeable ion Na ( $19.6 \text{ c mol}_c \text{ kg}^{-1}$ ) of the natural soil were higher than that of other ions like K, Ca and Mg (Table 1). The mass basis natural water content of the studied soil was 94.9 %.

### 2.3 Preparation of soil sample for slaking test

The flow chart for slaking test is given in Fig. 1. The slaking test was conducted at the Agricultural Land Research Laboratory, Graduate School of Environmental Science, Okayama University, Japan during February, 2009 following basically to Experimental Guide of Physical-Mechanical Properties of Soil (The Editing Committee of Experimental Guide of Physical-Mechanical Properties of Soil, JSIDRE, 1983). The natural soil was separated into two batches, one batch was air-dried and another was not dried (natural). Each batch of soil was mixed thoroughly and the air-dried batch was re-saturated. The soils were packed into stainless steel cylinders (2.5 cm height and 5 cm diameter) by pushing them into the soil. The specimens were kept in a desiccator at  $30^{\circ}\text{C}$  for drying treatment to attain different initial soil water contents of 60, 50, 40, 30, 20 and 10 % by weight. The weight of each specimen was monitored carefully until the desired water contents. The each water content treatment was replicated thrice. After completing water content adjustment the soil specimens were sealed and kept in a refrigerator.

Lastly, the each soil specimen was placed on the  $4.75 \text{ mm}$  sieve and immersed into tap water ( $\text{EC}$ :  $0.112 \text{ dS m}^{-1}$ , volume:  $9080 \text{ cm}^3$ ) for slaking test. After 24 hours immersion in the water the slaked (fell down through the sieve) and unslaked (remained on the sieve) soils were collected and weighted separately. The cations in the extract solution (Soil : Water = 1 : 5) from the slaked and the unslaked soils were measured by AAS. The exchangeable cations of the slaked and unslaked soils were also measured by the same method described previously.

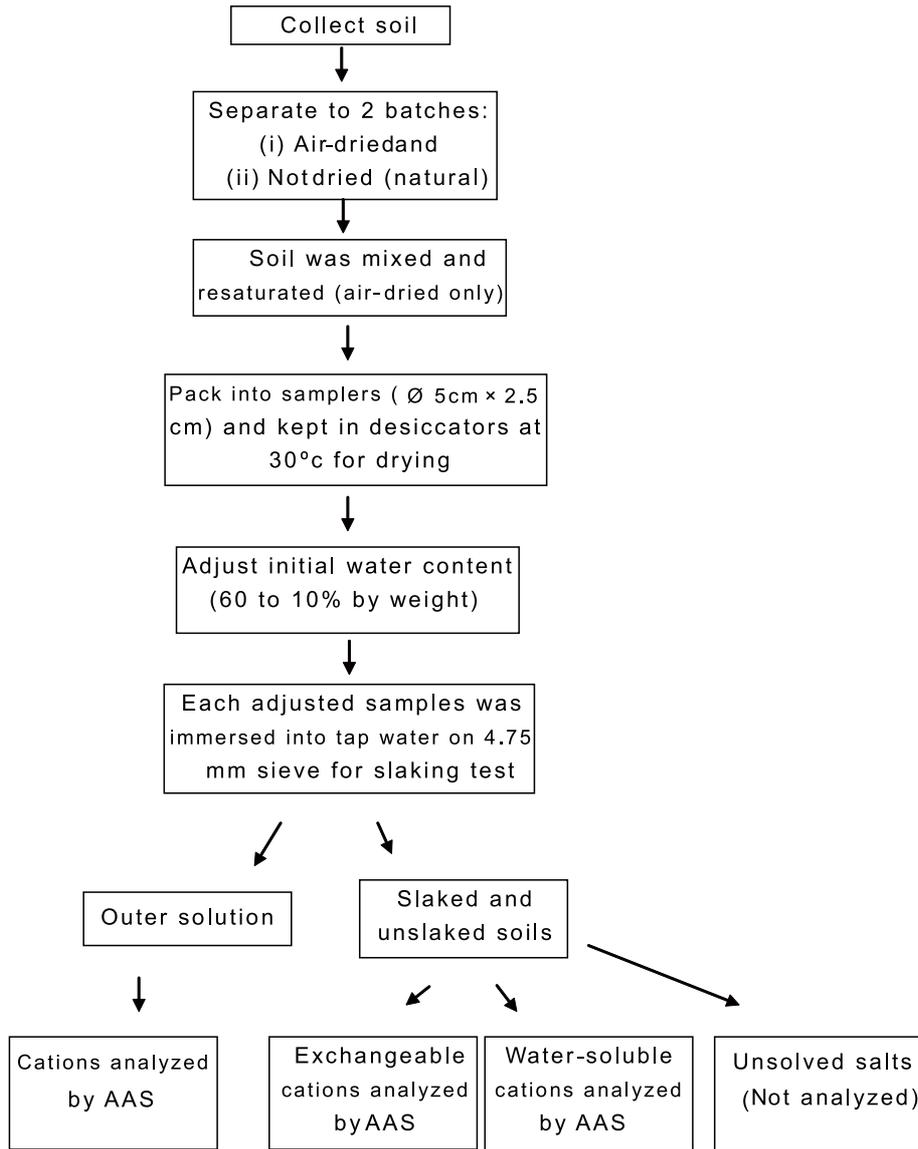


Fig. 1 Flow chart for slaking test.

#### 2.4 Calculation of slaking rate of soil

The slaking rate,  $SR$  (%) was calculated by using the following equation;

$$SR(\%) = s / (s + u) \times 100 \quad (1)$$

Where  $s$  represents the weight of the slaked soil and  $u$  indicates the weight of the unslaked soil.

#### 2.5 Calculation of cations in solution and soil

The salt released into outer solution ( $M_i$ ) was calculated by the following equation;

$$M_i = C_i \times V_w \quad (2)$$

Where  $C_i$  is concentration of the cations;  $V_w$  refers to the volume of the outer solution of the slaking test.

As the cation concentrations were measured on 1 : 5 solution ( $C_{1:5}$ ), the amount of a cation in the slaked soil,  $M_s$  is given by equation (3),

$$M_s = (C_{s1:5} \times 5 \times W_s) / \rho_w \quad (3)$$

Where  $W_s$  represents the weight of soil;  $\rho_w$  is the density of the water. Similarly, cation in the unslaked soil,  $M_u$  is given by equation (4);

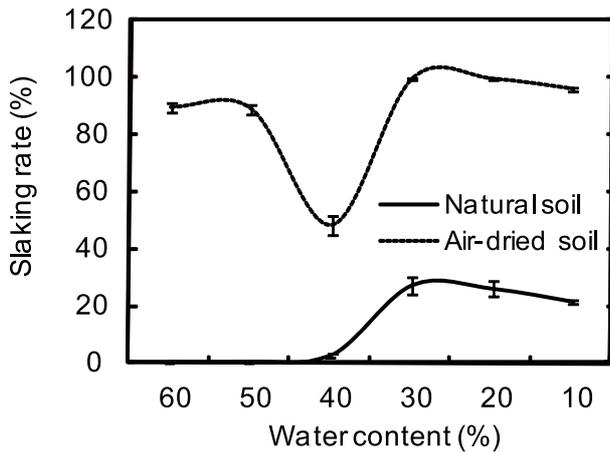
$$M_u = (C_{u1:5} \times 5 \times W_s) / \rho_w \quad (4)$$

The total cation remains in the soil,  $M_t$ , is given by sum of  $M_s$  and  $M_u$ .

$$M_t = M_s + M_u \quad (5)$$

Letting the amount of released Na in the outer solution as  $R_{Na}$ , then desalination rate of Na ion on soluble salt,  $DR$ , is defined by equation (6).

$$DR(\%) = R_{Na} / (R_{Na} + M_{t,Na}) \times 100 \quad (6)$$



**Fig. 2** Dependence of slaking rate against initial water contents after 24 hours immersion in water. Vertical bar indicates  $\pm$  SE of three replicates.

Where  $DR$  is the fraction of Na released into the outer solution divided by the sum of Na in outer solution, water-soluble Na in the slaked and the unslaked soils. It is noted that this  $DR$  does not include the exchangeable Na in the soil, nor the confined salt.

### 3. Results and discussion

For discussing the displacement of cations from a site to site, we specified the sites into four categories (phases): (1) free cations in outer solution, (2) water-soluble cations in soils (slaked and unslaked) and (3) exchangeable cations. In addition, some salts may remain in confined or stagnant pores, although the amount of that cannot be measured.

#### 3.1 Effect of initial water content on slaking rate

Dependence of slaking rate on water content is shown in Fig. 2. The bars in the figure show the standard error of three replicates.

##### 3.1.1 Natural soil

The slaking rates of the specimen at 60 and 50 % water content were only 0.15 and 0.16 %, respectively, after 24 hours immersion. It may be due to the sample was initially saturated and contained no entrapped air, resulting the low force of escaping air. Under the water content of 40 %, the slaking rate, 2.54 %, was higher than that of 50 %. This indicates that the natural soil started to slake below this water content. A significant change was observed at water content of 30 %. The slaking rate (27.3 %) was much higher in comparison with other water contents. It seems due to that the initial water content of 30 % was close to shrinkage limit and contained more air than that of 40 to 60 %. It resulted higher force of escaping air pressure, which is favourable condition for slaking. The slaking rate kept the almost same value (26.0 %) at water content of 20%.

##### 3.1.2 Air-dried soil

On the other hand, 88 – 89 % of the air-dried specimens were slaked at water contents of 60 and 50 % which in-

dicates that after experiencing air-drying, soil changed to slake much more easily. The slaking rate was very high (99 %) under 30 and 20 % in comparison with any other water contents. The slaking rate at water content of 10 % was comparatively higher than that of 60 and 50 and 40 % but lower than 30 and 20 % water content in both of natural and air-dried soils (Fig. 2). This is attributed to that the strong linkage developed between soil particles by the intensive drying, which might enhance resistance to slaking.

#### 3.1.3 Difference between natural and air-dried soil

The slaking rate of air-dried soil was higher than that of the natural soil at all water contents. It is due to that air-drying increased entrapped air than the natural soils at the same water content, resulting the higher force of escaping air pressure. Much more bubbles were observed during slaking of the air dried soil than the natural soil.

#### 3.2 Effect of initial water content on cations in the three phases

Table 2 and Table 3 show the variance of measurement on amount of shifted cations among three categories. They also express the precision of each cation measurement in different water contents. These tables reveal that the cations measurement of Na, Ca and Mg is statistically reliable enough because the range is below 25 % against the mean values. Note that the variance of K measurement in water-soluble phases was so large in comparison with other cations in both the natural and the air-dried soils. This is due to critically small values of K against precision of measurement, but contribution of K is not important in desalinization from saline soil.

#### 3.3 Cations released into outer solution after 24 hours immersion

Fig. 3 shows the cations released into outer solution after 24 hours immersion of different pre-drying treatment (natural and air-dried) of soils. The bars in the figure show range of the measured values, indicating the variance of measurement is small enough statistically. The figure shows that Na exists predominantly in the outer solution and the release of Na is maximum at water content of 30 %.

##### 3.3.1 Natural soil

At the lower water content of 20 and 10 %, the amount of Na released to outer solution ( $R_{Na} = 0.25 \text{ mmol g}^{-1}$  and  $0.25 \text{ mmol g}^{-1}$ , respectively) were high, and it was highest at 30 % ( $0.35 \text{ mmol g}^{-1}$ ). The  $R_{Na}$  at 60, 50 and 40 % water content were 0.185, 0.18 and  $0.19 \text{ mmol g}^{-1}$ , respectively. The difference in the total Na under different water content is mainly due to the amount of Na in the outer solution. The fractions of Na in outer solution were 74.6, 73.2, 76.7, 71.5, 70.1 and 65.9% at water content of 10, 20, 30, 40, 50, 60%, respectively. At water content of

**Table 2** Mean of range/average ratios on amount of cations in three phases in natural soil.

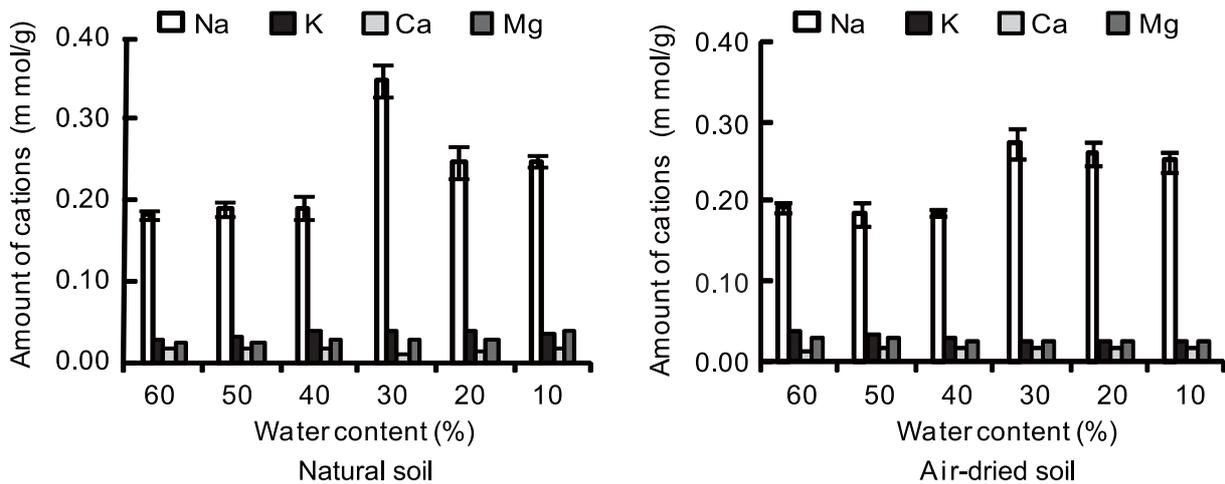
Phases	Water content	Na	K	Ca	Mg
		*IV (%)	IV (%)	IV (%)	IV (%)
Outer solution	60~10%	17.5	14.3	23.3	16.1
Exchangeable	60~10%	15.3	25.6	16.8	13.4
Water-soluble	60~10%	22.8	75.7	0.18	15.5

\* IV (Index of Variance) = mean {range (maximum value – minimum value)/average} on cation concentration of different water content. Measurements were replicated thrice on each water content, i.e., n = 18.

**Table 3** Mean of range/average ratios on amount of cations in three phases in air-dried soil.

Phases	Water content	Na	K	Ca	Mg
		*IV (%)	IV (%)	IV (%)	IV (%)
Outer solution	60~10%	17.7	14.1	23.4	18.1
Exchangeable	60~10%	8.5	12.8	12.6	17.5
Water-soluble	60~10%	17.3	75.7	2.30	1.30

\* IV (Index of Variance) = mean {range (maximum value – minimum value)/average} on cation concentration of different moisture content. Measurements were replicated thrice on each water content, i.e., n = 18.



**Fig. 3** Cations released into outer solution after 24 hours immersion in different pre-drying treatments. Vertical bar indicates  $\pm$  SE of three replicates.

30%, maximum Na was released from confined or stagnant pores to outer solution because the maximum slaking occurred and collapsed aggregates at this water content (Fig. 2). At water content of 10 %, samples slaked in short time and the  $R_{Na}$  was low as  $0.25 \text{ mmol g}^{-1}$ . It was shown that very dry condition and quick slaking did not contribute the more Na release from the soil.

### 3.3.2 Air-dried soil

At water content of 30 and 20 %, the  $R_{Na}$  was 0.27 and  $0.26 \text{ mmol g}^{-1}$ , respectively. On the other hand, when the soil was in the driest condition of 10 % water content slaking made limited contribution to  $R_{Na}$  ( $0.25 \text{ mmol g}^{-1}$ ) which was equal to that of the natural soil.

### 3.3.3 Difference between natural and air-dried soil

Both the natural and air-dried soil followed the same trend for releasing Na in relation to the initial water contents. The water content above 40 % showed less  $R_{Na}$ , and below water content of 30 %  $R_{Na}$  was high. But the effects were more pronounced in the natural soil. The maximum release of Na occurred around at the coincident water content as maximum slaking. The results indicate that higher water content and too rapid slaking at low water contents were not efficient for removing Na from the soil block.

In terms of other cations release like Ca, Mg and K, all the soils show almost the similar trends. Note that very little amount of Ca and Mg comes out to outer solution. The release of cations to outer solution in soils followed the order of  $Na \gg K > Mg > Ca$ , and drying did not affect the composition of K, Mg and Ca except for a slight increase in Mg and slight decrease in K in a few cases (Fig. 3).

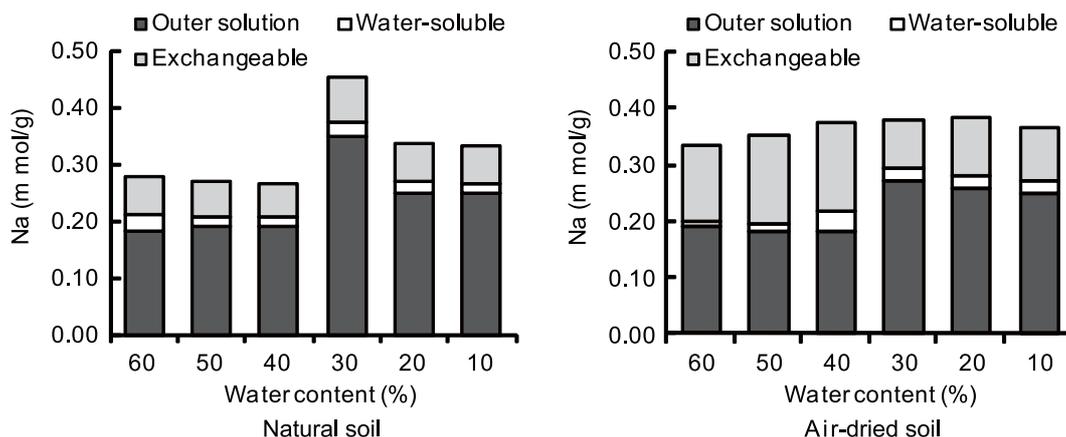


Fig. 4 Amount of Na in outer solution and left in soils after 24 hours immersion under different initial water contents.

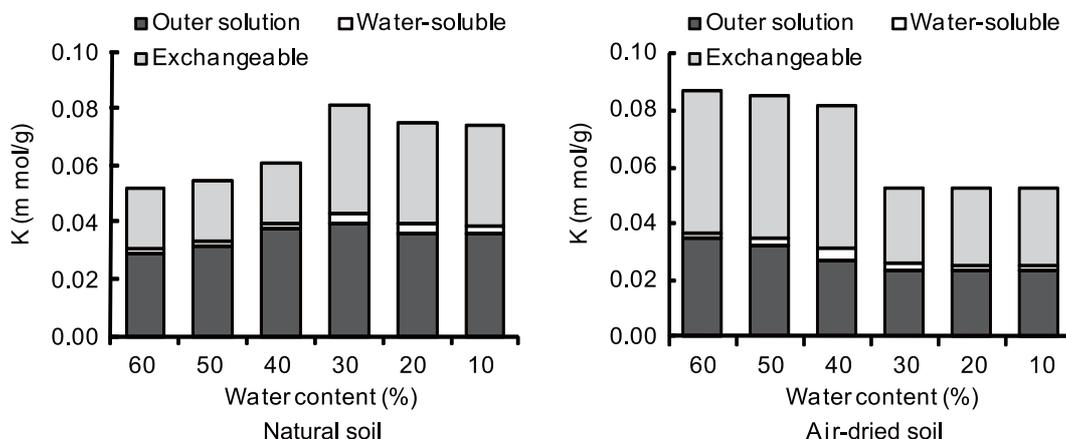


Fig. 5 Amount of K in outer solution and left in soils after 24 hours immersion under different initial water contents.

### 3.4 Impacts of slaking and drying on water-soluble cations in soils

Fig. 4, 5, 6 and 7 shows the sites and amounts of each cation (Na, K, Ca and Mg) after 24 hours immersion, respectively. The site where the cations exist is divided into four categories; outer solution, exchangeable state and water-soluble state in the soil and salts in confined pores which cannot be measured. It is seen that the fraction of the water soluble state is relatively very small. Among them Na showed much higher values than the other cations, showing slight increase with drying. We did not find any significant differences in amount of other water-soluble cations like Ca, Mg and K in the slaked and unslaked soils in almost all the cases.

#### 3.4.1 Natural soil

In terms of water-soluble Na (after 24 hours immersion) in slaked and unslaked soils, more Na (8 to 10 %) existed in the soil at higher water content (60 %). This is because some of Na stayed in stagnant part inside the soil in higher water contents. On the other hand, when soil slakes at lower water content the Na staying in soils was lowest proportion (5 %) which might be due to the Na stayed mainly

close to the surface. It was found higher water content was not effective from the stand point of Na release from soil. The water-soluble K, Ca and Mg in soils were in small amounts ( $< 0.02 \text{ mmol g}^{-1}$ ) in both the higher and lower water contents.

#### 3.4.2 Air-dried soil

The higher water content of 60 and 50 % held less Na (2 to 3 %) as water soluble than the natural soil which means most of the Na released into outer solution. This is because, the air-dried soil at that water content slaked more than the natural soil. It is due to decrease in the Na staying in the stagnant part inside the aggregates. The water-soluble Ca and Mg in air-dried soil followed the same trend as the natural soil.

#### 3.4.3 Difference between natural and air-dried soil

At lower water content the air-dried soil held slightly more water-soluble Na than that of the natural soil. But the amounts of water soluble cations were affected very little by the drying. The amount of water-soluble cations followed the order of  $\text{Na} \gg \text{K} > \text{Mg} > \text{Ca}$  in all these soils after 24 hours immersion.

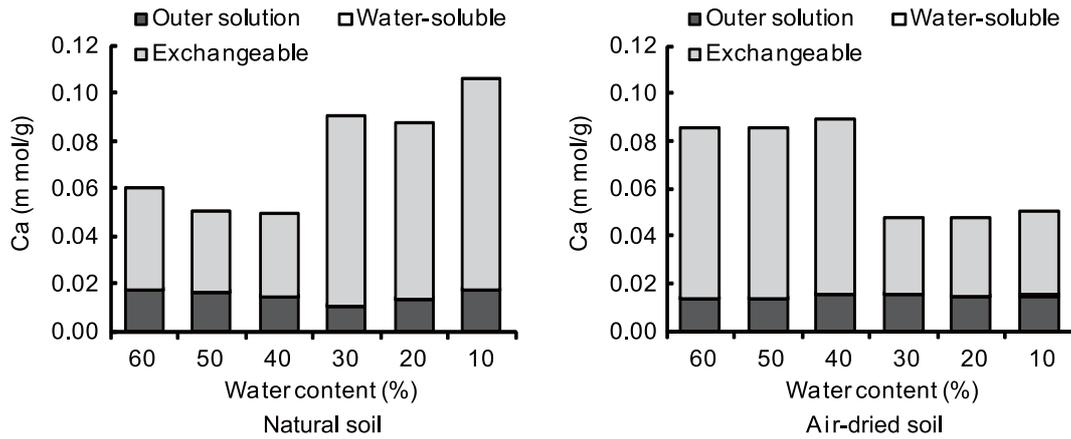


Fig. 6 Amount of Ca in outer solution and left in soils after 24 hours immersion under different initial water contents.

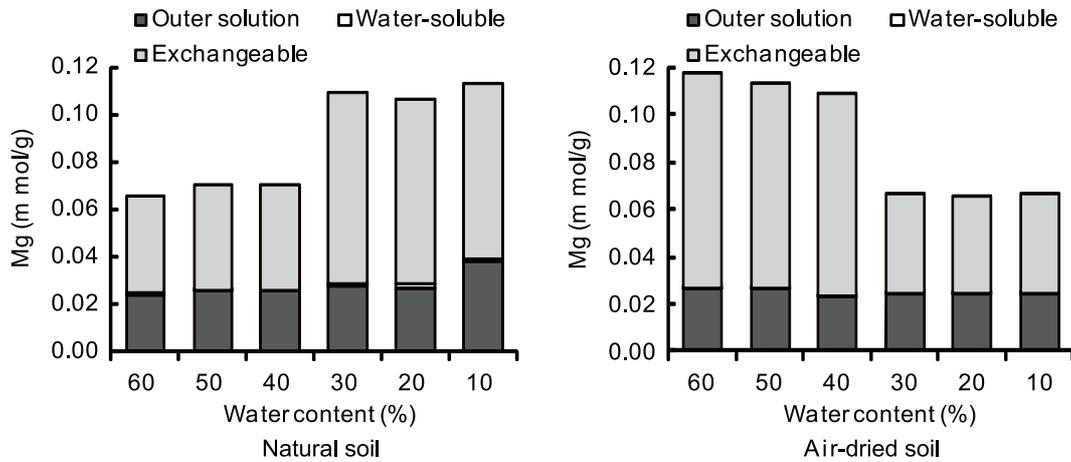


Fig. 7 Amount of Mg in outer solution and left in soils after 24 hours immersion under different initial water contents.

### 3.5 Impacts of slaking and drying on exchangeable cations in soils

#### 3.5.1 Natural soil

In terms of exchangeable cations, Na was slightly affected by slaking and drying after 24 hours immersion (Fig. 4). The lower water content held slightly higher exchangeable Na than higher water contents, especially at 30%. It means a part of Na on exchange sites was replaced by the other exchangeable cations during drying and slaking under higher water content. Exchangeable  $K^+$  below water content of 30% was higher than that of above 40% water contents. Most of the  $Ca^{2+}$  and  $Mg^{2+}$  stay in exchange site (60 to 80%) and showed much higher proportion at lower water contents in the natural soil (Fig. 6 and Fig. 7).

#### 3.5.2 Air-dried soil

The air-dried soil showed the different trends in remaining exchangeable Na from the natural soil. Note that the cations exist in exchangeable state at highest amount at water content of 40% (Fig. 4). This result is very special, the soils at this water content did not slake well in comparison with other water contents (Fig. 2). Whereas, the air-dried soils show exchangeable  $K^+$  is low in lower water contents different from that of Na (Fig. 5). In terms of  $Ca^{2+}$

and  $Mg^{2+}$ , the air-dried soil showed similar trends to  $K^+$ , the exchangeable  $Ca^{2+}$  and  $Mg^{2+}$  was in lower proportion at lower water contents (Fig. 6 and Fig. 7).

#### 3.5.3 Difference between natural and air-dried soil

The exchangeable  $Na^+$  was mainly replaced by  $Ca^{2+}$  and  $Mg^{2+}$  at lower water contents. The results also indicate that the exchangeable cations were increased by the effect of drying (ion concentration in equilibrium solution was condensed by drying). This is because the  $Ca^{2+}$  and  $Mg^{2+}$  ions are more strongly bonded with exchange sites of soil particles due to their higher valence; on the other hand,  $K^+$  has strong binding capacity with clay particles in comparison with  $Na^+$  ions.

The holding of exchangeable cations followed the order of  $Na^+ > Mg^{2+} > Ca^{2+} > K^+$  except for a minor increase in  $Mg^{2+}$  and slight increase in  $Ca^{2+}$  than  $Na^+$  in few cases under the natural soil. It is due to the presence of insoluble Ca and Mg salts in the original polder soil.

#### 3.6 Desalination rate to outer solution

Fig. 8 shows the desalination rate (*DR*) to outer solution in different pre-drying treatments of soils. In this case, we considered the Na released into outer solution and

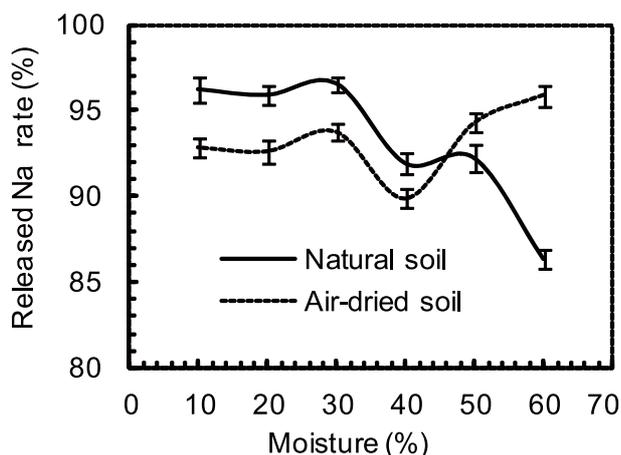


Fig. 8 Desalination rate or released water-soluble Na from soils after 24 hours immersion under different initial water contents. Vertical bar indicates  $\pm$  SE of three replicates.

water-soluble Na remaining in slaked and unslaked soils after 24 hours immersion. It is a measure of water soluble salt released to outer solution from all of water soluble salt in the soil block.

### 3.6.1 Natural soil

It was shown that desalination rate was higher at lower water content after 24 hours emersion. At higher water contents (60, 50 and 40 %) the *DR* was low (*DR* = 86, 92 and 91 % respectively) than that of lower water contents (30, 20 and 10 %; *DR* = 96, 95 and 96 % respectively).

### 3.6.2 Air-dried soil

Both the higher and lower water contents showed high desalination rate except for 40 % (*DR* = 90 %). However, if the soil was in excessively dry condition (10 % water content), slaking did not release more Na, resulting the low *DR* (93 %), which might be due to the strongly trapped Na between the soil particles during drying.

### 3.6.3 Difference between natural and air-dried soil

The desalination rate of the air-dried soil showed similar trend as the natural soil under lower water content, but showed the opposite trend at higher water contents. In the natural soil, at higher water content, soil did not slake well, on the other hand air-dried soil slaked very quickly at the same water content. The trend was similar to that of slaking (Fig. 2).

The whole result indicates that the desalination rate is somewhat affected by the initial water content and by the intensity of pre-drying. The soluble salt release to outer solution is slightly enhanced by soil slaking. Shamim and Akae (2010) had also reported that the salt release is linearly proportional to the slaking rate in both of the natural and the air-dry soils. The higher salt release was caused by higher slaking rate. At slaking rate is almost zero (60 and 50 % moisture contents) in the natural soil, the proportion

of salt released into water were 86.4% after 24 hours immersion. It increased to 96.6 % at 27 % slaking rate in the natural soil. For the air-dried soil, it is highest (93.8 %) at slaking rate close to 100 %. It means that under the optimum water contents, soil slaking can enhance releasing of soluble salt from the natural soil by 10.2 %. The results suggested that the lower water content and the slower slaking is more efficient for desalinating of saline soil.

## 4. Conclusions

In this study, the Na in the outer solution surrounding the slaked soil blocks were measured, which is a substantial measure of the amount of Na exclusion from the soil block. In addition, sites and states (exchange sites and soluble salts) of cations in soil were examined. The following facts were revealed by this study:

- (1) Na was predominantly affected by slaking (and drying) in terms of releasing cations. However, there were not any special differences between water content and released water-soluble cations like Ca, Mg and K.
- (2) Most of the  $\text{Ca}^{2+}$  and  $\text{Mg}^{2+}$  stay in exchange sites (60 to 80 %) in soil and very few come out in outer solution.
- (3) The exchangeable cations of the natural soil were increased by the effect of drying. This revealed that shift of cations were caused to exchange phase by drying.
- (4) The lower water content (30 %) released more Na, and at the minimum slaking rate the release of Na was lowest in both the natural and air-dried soils.
- (5) However, when the soil was too dry condition (10 % water content) and slaking was very rapid, Na release was not enhanced more.

But the further study and research in this challenging field is encouraged in order to discover the most effective and applicable desalination method for the soil.

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## 要 旨

スレーキングの機構は、水の流入による土壤団粒の破壊であり、土壤が塩分を含む時、塩分を解放する過程を伴う。本論文の目的は、異なる初期含水状態での除塩において、スレーキングと乾燥が、陽イオンの外液中への排出と状態の移動に及ぼす影響を述べることである。初期含水比を変えた（60, 50, 40, 30, 20, 10 % 重量含水比）自然土と風乾土へのスレーキングの効果を評価するため、スレーキング試験を行った。24 時間の水浸後、自然土と風乾土の全てのケースで、Na が卓越して排出された。最適スレーキング含水比にほぼ等しい比較的低い含水比（30 %）で最大の Na が解放され、スレーキング率が最低の含水比で、Na の排出は最も低かった。しかしながら、低すぎる含水比（10 %）は、それ以上の Na の解放に寄与しなかった。一方、外液中の他の陽イオン Ca, Mg, K の解放と初期含水比の間には特別な関係は認められなかった。ほとんど（60～80 %）の Ca と Mg は、交換性サイトに停滞し、外液中には僅かしか出て来ない。スレーキング後の土に残存する水溶性陽イオンは、 $Na \gg K > Mg > Ca$  の順であり、これに対し、交換態の陽イオンの量は  $Na > Mg > Ca > K$  の順であった。全体として、外液中に解放された Na 量は自然土の方が風乾土よりも多かった。最適スレーキング含水比と、よりゆっくりとしたスレーキングが土壤からの Na の除塩により効率的であることが示された。

キーワード：土壤のスレーキング， 土壤水分状態， 陽イオンの解放， 除塩， 交換態