

Impact of monovalent cations on soil structure. Part II. Results of two Swiss soils

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Abstract. In this study, we investigated the impact of adding solutions with different potassium and sodium concentrations on dispersible clay, water retention characteristics, air permeability, and soil shrinkage behaviour using two agricultural soils from Switzerland with different clay content but similar organic carbon to clay ratio. Three different solutions (including only Na, only K, and the combination of both) were added to soil samples at three different cation ratio of soil structural stability levels, and the soil samples were incubated for one month. Our findings showed that the amount of readily dispersible clay increased with increasing Na concentrations and with increasing cation ratio of soil structural stability. The treatment with the maximum Na concentration resulted in the highest water retention and in the lowest shrinkage capacity. This was associated with high amounts of readily dispersible clay. Air permeability generally increased during incubation due to moderate wetting and drying cycles, but the increase was negatively correlated with readily dispersible clay. Readily dispersible clay decreased with increasing K, while readily dispersible clay increased with increasing K in Iranian soil (Part I of our study). This can be attributed to the different clay mineralogy of the studied soils (muscovite in Part I and illite in Part II).

Keywords: air-permeability, sodium, potassium, soil shrinkage, specific volume, turbidity

INTRODUCTION

Salt-affected soils are found in most climatic zones of the world, although salinisation problems mainly occur in arid and semi-arid regions. The extent and nature of salt problems can have various sources. It can originate from mineral weathering, stored salts, aeolian salinity, rainfall, and irrigation with saline/sodic water. Salinisation is a complicated process involving seasonal water and salts movement in soils, and interactions with groundwater.

Sodium salts are prevailing in many salt-affected soils of the world (Rengasamy, 2006). Monovalent cations, such as sodium (Na) and potassium (K) can create clay dispersion and swelling. Swelling takes place when the concentration of monovalent cations is high, while dispersion will occur in soils with low cation concentration (Shainberg and Letey, 1984; Sumner, 1993). Dispersion (also termed deflocculation) is the consequence of an increase in the thickness of the diffuse double layer, accompanied by a decrease in the attractive forces between clay particles (Menner *et al.*, 2001). Swelling and dispersion of clays has significant (mostly negative) effects on soil structure and associated soil functions (fluid-transport functions) (Chaudhari and Somawanshi, 2004): swelling reduces soil pore sizes and dispersed clay may clog soil pores (Frenkel and Rhoades, 1978).

Soil structure is central for many ecosystem services, including (agricultural) productivity and flood control. Soil structure has two important characteristics (Kay, 1990): form, *i.e.* the geometrical arrangement of soil particles and pores, and stability, *i.e.* resistance against stress. A range of soil functions are largely governed by soil structure, such as the soil fluid transport capability that regulates the soil gas (aeration) and water balance (infiltration). Such functions can, therefore, be used as indicators of the quality of soil structure and of soil-structure changes caused by soil management practices (tillage, crop rotation, and fertilisation), soil compaction or salinisation (Ball, 1981; Blackwell *et al.*, 1990; Iversen *et al.*, 2001). Fluid transport properties are typically more sensitive to modifications of soil structure than, for example, water retention or porosity,

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because transport functions are not only affected by pore size (distribution) but also by pore connectivity, continuity and tortuosity. The shrinkage characteristics of soil could contain information on both porosity and structural stability (Schäffer *et al.*, 2013). Shrinkage curves (soil volume as a function of soil moisture content; Braudeau *et al.*, 1999) have therefore been used to assess the structural quality of soils (Johannes *et al.*, 2017) and to quantify soil management and compaction effects on soil structure (Schäffer *et al.*, 2008; 2013). Sou/Dakouré *et al.* (2013) used shrinkage curves to assess the impact of irrigation water containing different concentrations of salts on the physical quality of a sandy loam soil in Burkina Faso.

Most investigations on the impact of salinity on clay dispersion, soil structure and stability have concentrated on the effect of highly exchangeable Na (Rengasamy, 2002). Exchangeable K can create similar effects as Na on soil structure, but it has received less attention than Na because concentrations of K are typically low in salt-affected soils (Rengasamy and Marchuk, 2011). K is one of the most important nutrients for plant growth and is usually added into soils as a fertiliser. The impact of exchangeable K on soil structure has been reported in the literature as being equal or less negative than the impact of Na (Chen *et al.*, 1983; El Swaify *et al.*, 1970). However, K in the exchange complex has been shown to affect clay dispersion as well, even at small amounts of exchangeable Na (Arienzo *et al.*, 2009; Emami *et al.*, 2014; Rengasamy, 2006; Robbins, 1984; Smiles, 2006; Subba Rao and Rao, 1996).

The objective of the present study was to investigate the impact of K and Na on soil structure and its stability for two soils with contrasting texture from northern Switzerland. The soil samples were incubated for one month using three types of solutions (Na only, K only, and a solution with both Na and K) with different cationic concentrations. The amount of readily dispersible clay (RDC), air-permeability (k_a) and soil shrinkage characteristics were measured after one-month incubation. We then discuss the role of clay mineralogy behind the impact of K on soil structure, considering the results of the present study and the results of our study of soil from Iran (Part I of the series of papers).

Table 1. Selected physical and chemical soil properties

Soil texture	Clay	Silt	Sand	OC	OC/Clay	EC ($\mu\text{S cm}^{-1}$)	pH	CEC	K	Na	Ca	Mg	Dominant clay type*
Si l	22.0	53.7	24.3	1.7	0.07	229	7.8	17.5	0.3	0.02	15.5	1.2	Illite
cl	44.7	34.7	15.3	3.1	0.07	253	6.1	37.8	0.2	0.07	23.1	2.7	Illite

OC – organic carbon content, EC – electrical conductivity, CEC – cation exchange capacity (*Peters, 1969).

MATERIAL AND METHODS

Soil samples were collected from the 0-0.3 m depth of two agricultural fields located at the Agroscope Research Institute in Zürich, northern Switzerland (47.3°N latitude, 8.5°E longitude and 408 m a.s.l. altitude). We selected two soils with different clay content, but with a similar ratio of organic carbon (OC) to clay content: a clay soil with 45% clay, below referred to as ‘cl’, and a silty loam with 22% clay, below referred to as ‘si l’. Both soils had an OC/Clay ratio of *c.* 0.07. The basic characteristics of the soils are presented in Table 1. Soil texture was determined using the pipette method (Gee and Bauder, 1986), and soil organic carbon was measured using the wet oxidation method (Walkley and Black, 1934). Electrical conductivity (EC) and pH were determined using soil water ratios of 1:2.5 and 1:3.3, respectively (Richards, 1954). Cation exchange capacity (CEC) and the concentration of exchangeable cations were determined by extracting the soils with a 0.1 M BaCl₂ solution, containing 0.03 M Triethanolamine and 0.015 M HCl, and with the pH adjusted to 8.1. Ca and Mg were measured by F-AAS (Flame-atomic absorption spectroscopy), and K and Na were measured by F-AES (Flame-atomic emission spectroscopy) (Rouessac and Rouessac, 2007).

In order to remove stones and clods, the soils were sieved (< 10 mm) without crashing, placed into cylinders (5 cm diameter, 5 cm height; 100 cm³), and prepared at a bulk density corresponding to a relative bulk density, BD_{ref} , of 0.7. The relative bulk density is a measure of the soil compactness and allows comparisons across soil textures, and was defined here as the ratio of actual bulk density to the Proctor maximum density, where the latter was estimated according to Naderi-Boldaji *et al.* (2016). The bulk densities were 1.18 and 1.04 g cm⁻³ for the si l and cl soil, respectively.

The soil samples were incubated with salt solutions for one month. We considered three types of solutions: only Na, only K, and both Na and K; and three levels of concentrations for each solution type with values for CROSS of 15, 25 and 35. This resulted in a total of 3 solution types × 3 concentration levels = 9 treatments (Table 2). The same treatments were applied to both soils. The electrical conductivity (EC) of the solutions was calculated from total cation concentrations (TCC) as $EC \text{ (dS m}^{-1}\text{)} \approx TCC \text{ (mmol)}$

Table 2. Cation concentrations of the treatment solutions

Treatment	K	Na	Ca	Mg	EC _{tr} (dS m ⁻¹)	CROSS _{tr}
	(mmol _c l ⁻¹)					
Na-1	0	14	1	1	1.5	15
Na-2	0	23	1	1	2.5	25
Na-3	0	31	1	1	3.3	35
K-1	24	0	1	1	2.6	15
K-2	40	0	1	1	4.2	25
K-3	56	0	1	1	5.8	35
(Na+K)-1	12	7	1	1	2.0	15
(Na+K)-2	20	11	1	1	3.3	25
(Na+K)-3	28	16	1	1	4.6	35
Control	0	0	0	0	0	0

EC_{tr} – electrical conductivity of the treatment solution, CROSS_{tr} – cation ratio of soil structural stability of the treatment solution.

l⁻¹)/10. The range of Na concentrations was between 6.7 and 31.3 mmol_c l⁻¹, and the K concentrations were in the range of 11.9 to 55.9 mmol_c l⁻¹. Constant concentrations of Ca and Mg were considered at each CROSS level, as we did not aim to assess the impact of divalent cations on soil structure. The sum of the concentrations of Ca and Mg in the treatment solutions was larger than the swelling threshold concentration of 0.3 mmol l⁻¹ defined by Quirk and Schofield (1955) for mixed solutions: 0.5 and 0.5 mmol l⁻¹ for CaCl₂ and MgCl₂, respectively. To quantify the flocculation and dispersing power of our solutions on soil structure, we calculated the cation ratio of soil structural stability (CROSS) as (Rengasamy and Marchuk, 2011):

$$CROSS_{tr} = \frac{Na + 0.56K}{\sqrt{\frac{Ca + 0.6Mg}{2}}}, \quad (1)$$

where: the concentrations of cations are in mmol_c l⁻¹ and the subscript ‘tr’ indicates ‘treatment solution’.

The solutions were added to the soil samples by capillary rise from the bottom, thereby reaching water content close to saturation. Four replicates (*i.e.* four cylinders) per treatment were used. The soils in the cylinders were exposed to moderate drying and wetting cycles during the one month incubation. The drying process at room temperature (20-25°C) continued only up to the water content corresponding to field capacity (100 hPa matric suction), and this was ensured by monitoring the weight of the samples on a daily basis. The weight of each sample at 100 hPa matric suction was measured before the start of the incubation.

The moderate drying also helped to avoid the creation of gaps between soil and cylinder walls. For the wetting, distilled water with a volume corresponding to the pore volume between saturation and 100 hPa was added to the plates on which the cylinders were placed.

The following measurements on the soil samples were performed after one month of incubation: concentrations of water soluble and exchangeable K, Na, Ca and Mg, the amount of readily dispersible clay (RDC), water retention, air permeability, shrinkage characteristics and the coefficient of linear extensibility (*COLE*). The methods are described in detail in the following sections. Also, CROSS, the sodium adsorption ratio (*SAR*), the potassium adsorption ratio (*PAR*), exchangeable sodium percentage (*ESP*), exchangeable potassium percentage (*EPP*) and K:Na ratios were calculated from the concentrations of the cations.

The four soil samples per treatment and soil texture were divided as follows: two randomly selected samples were used for destructive measurements, and the other two samples were kept intact. The amount of readily dispersible clay, CROSS, SAR, PAR, ESP, EPP and K:Na ratios were measured on the former (*i.e.* destructive measurements). All the other measurements were done on the intact cylindrical samples.

The amount of readily dispersible clay was obtained from turbidity measurements following the method described by Kay and Dexter (1990) and Watts *et al.* (1996). About 5 g of air-dry soil was shaken with 125 ml of distilled water in a standardised way. The suspension was allowed to stand for 18 h for the larger particles to sediment, leaving only colloidal (mostly clay) particles in suspension. 30 ml of

suspension was taken from the centre of each sample with a pipette and was transferred to a glass turbidity cell. The turbidity was measured using a Hach 2100N Laboratory Turbidimeter and recorded in Nephelometric Turbidity Units (NTU).

The cation concentrations were measured on sieved (<2 mm) soil samples. The water soluble cations (K, Na, Ca and Mg) were obtained using the ICP-OES analysis method (Rouessac and Rouessac, 2007). The exchangeable cation concentrations were measured using exchange of the cations with Barium (0.1 M BaCl₂ solution) from the exchange solution, and Ca and Mg were measured by F-AAS, and K and Na were measured by F-AES (Rouessac and Rouessac, 2007). The sodium adsorption ratio (*SAR*) was calculated as (Richards, 1954):

$$SAR = \frac{Na^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad (2)$$

The potassium adsorption ratio (*PAR*) was calculated as (Chen *et al.*, 1983):

$$PAR = \frac{K^+}{\sqrt{\frac{Ca^{2+} + Mg^{2+}}{2}}} \quad (3)$$

where: the concentrations of water soluble cations in Eqs (2), (3) were measured in soil solution (mmol_c l⁻¹). The *EPP* and *ESP* were calculated as (Richards, 1954):

$$EPP = \frac{K_{ex}}{CEC} 100, \quad (4)$$

$$ESP = \frac{Na_{ex}}{CEC} 100, \quad (5)$$

where: Na_{ex} and K_{ex} are concentrations of exchangeable cations (cmol_c kg⁻¹) and *CEC* is the cation exchange capacity. This was determined by extracting the soils with a 0.1 M BaCl₂ solution, containing 0.03 M Triethanolamine and 0.015 M HCl and with the pH adjusted to 8.1 (Rouessac and Rouessac, 2007).

Air permeability was measured using a steady-state method on the intact soil core samples as described by Martínez *et al.* (2016), at a water content corresponding to a matric suction of 100 hPa. The soil at the very edge of the core was carefully pressed to the cylinder walls in order to minimise leakage of air between the soil and the cylinder wall (Ball and Schjønning, 2002). The airflow was recorded when the volumetric flow rate was stabilised at a pressure of 2 hPa. Air permeability (*k_a*) was calculated from the volumetric flow rate and the applied pressure head using Darcy equation, as:

$$k_a = \frac{-Q_s \eta}{\Delta p A_s} \quad (6)$$

where: *Q* is the volumetric flow rate (m³ s⁻¹), *l_s* is the height of the soil sample (m), *η* is the dynamic air viscosity (Pa s), *Δp* is the difference in air pressure (Pa) and *A_s* is the cross-sectional area of the soil sample (m²).

Soil shrinkage and water retention characteristics were measured on the intact soil core samples by monitoring the weight and the height of the samples, and the matric potential in the samples during drying from near saturation (matric suction of 10 hPa) to air-dry condition was measured using a similar set-up to that described by Boivin *et al.* (2004). The samples were placed on electronic balances with a precision of 0.01 g. Weight, height (using calibrated displacement transducers with a resolution of 1 μm) and matric suction (up to *c.* 800 hPa, using microtensiometers with ceramic cups of 2 cm length and 0.2 cm diameter installed at mid-height of the samples) of the samples were recorded at intervals of 5 min. The measurements were terminated when the sample reached constant weights (Schäffer *et al.*, 2008), which took about one week for our samples. The dry sample volumes were then determined by the plastic-bag method” by means of hydrostatic weighing as described by Boivin *et al.* (1990) and Schäffer *et al.* (2008). To obtain an accurate value of the sample volume, the procedure was repeated five times per sample, and the average of the five measurements was used. Finally, the samples were dried in an oven at 105°C for 24 h to obtain the oven-dry weight and to calculate bulk density.

In order to characterise the magnitude of soil volume change after drying, we calculated *COLE*, described by Gray and Allbrook (2002) as:

$$COLE = (v_{330\text{hPa}} - v_{\text{oven-dry}})^{\frac{1}{3}} - 1, \quad (7)$$

where: *v*_{330hPa} is soil volume at a matric suction of 330 hPa (*i.e.* a value typically considered as field capacity in the US) and *v*_{oven-dry} is the soil volume at oven dry condition. Here, we slightly modified Eq. (7) and calculated *COLE* for different matric suction ranges: *COLE*₁₀₋₃₃₀ considering volume changes between 10 and 330 hPa, *COLE*_{330-ad} considering volume changes between 330 hPa and air-dry condition, and *COLE*_{10-ad} considering volume changes between 10 hPa and air-dry condition.

The data were analysed using a general linear model (GLM) for a factorial experiment with a completely randomised design, with four replications per treatment. Analyses were made with the MINITAB 16 software. ANOVA (simple effects and multiple comparisons) were done using the least significant difference (LSD) test (Bonferroni method) at the significance level *p* < 0.05. Linear relationships between parameters were determined using regression analysis.

RESULTS AND DISCUSSION

Relationships between RDC and K concentration, Na concentration, K:Na ratio, and cationic indicators (*CROSS*, *SAR*, *PAR*, *ESP* and *EPP*) are shown in Figs 1-3. The results of the analysis of variance (ANOVA) for RDC are shown in supplementary Table S1. The values of RDC measured in our study were in the range of 1100 to 10100 NTU. Although the two soils had similar OC/Clay ratios, RDC was higher in the cl soil (45% clay) than in the sil soil (22% clay) (Figs 1-3). Clay dispersion was high in the cl soil despite the relatively high organic carbon content. Our results are in accordance with data presented by Levy and Torrento (1995) and Etana *et al.* (2009), who studied soils with different clay contents and observed that RDC was

higher in the soils with higher clay contents. Dexter and Czyż (2000) reported that RDC decreased with increasing soil organic carbon content. However, their soils were mostly sandy soils.

For both soils of our study, negative relationships were obtained between RDC and K concentration (Fig. 1a), and positive correlations between RDC and Na concentration (Fig. 1b). Furthermore, negative correlations were obtained between RDC and K:Na ratios for both soils, although these were not significant (Fig. 1c). Positive correlations were found between RDC and *CROSS* (Fig. 2a) and RDC and *SAR* (Fig. 2b), while negative relationships were obtained between RDC and *PAR* (Fig. 2c). Since the concentrations of Ca and Mg did not change between treatments (Table 2), *SAR* (Eq. (2)) is a function of Na and *PAR* (Eq. (3)) is

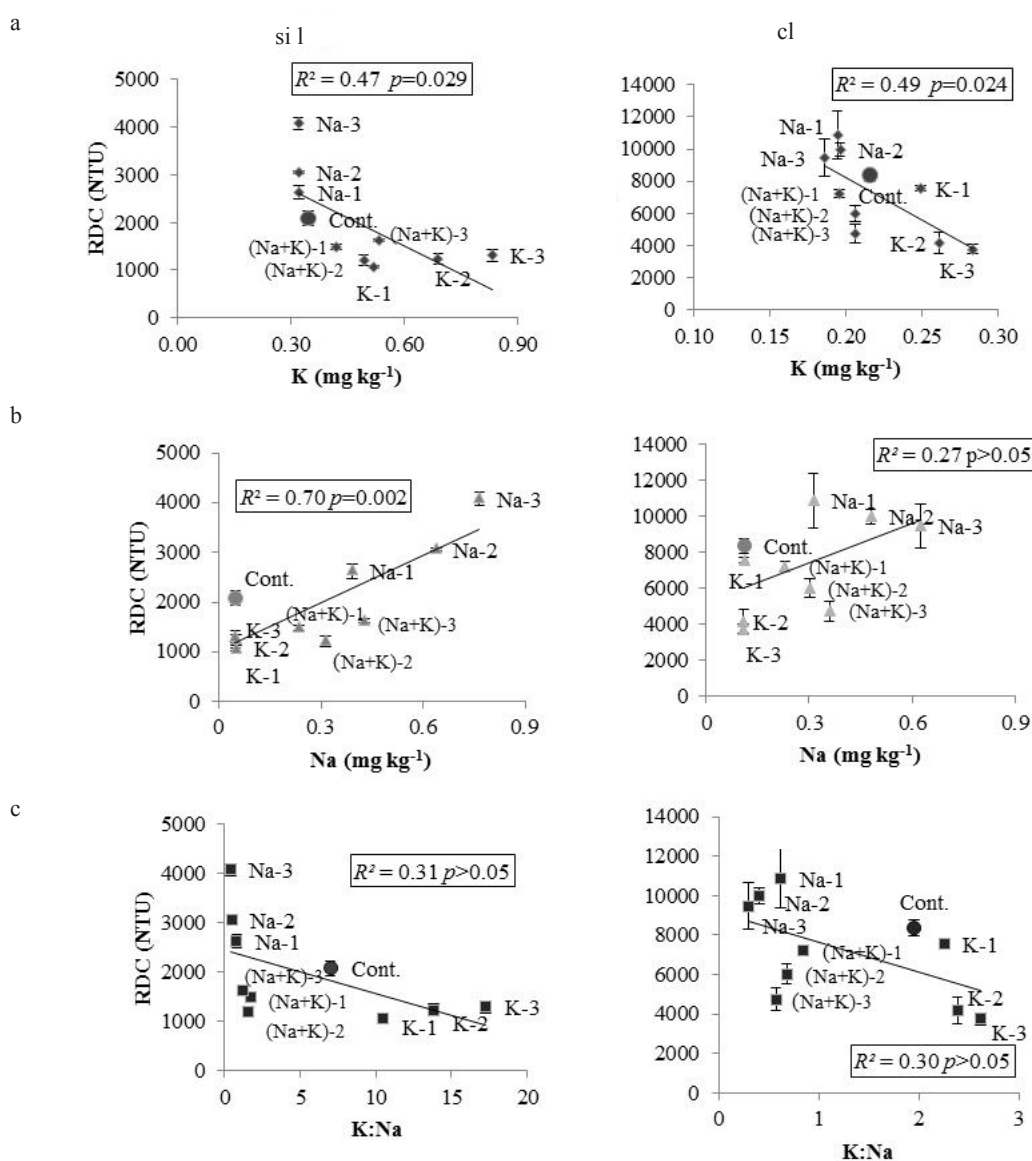


Fig. 1. Amount of readily dispersible clay, RDC in units of NTU, as a function of: a – K concentration, b – Na concentration, c – K:Na ratio, for the silt loam (left) and the clay soil (right). Labels next to the data points indicate treatments (Table 2), cont. indicates control. Note the different scales for RDC for the two soils.

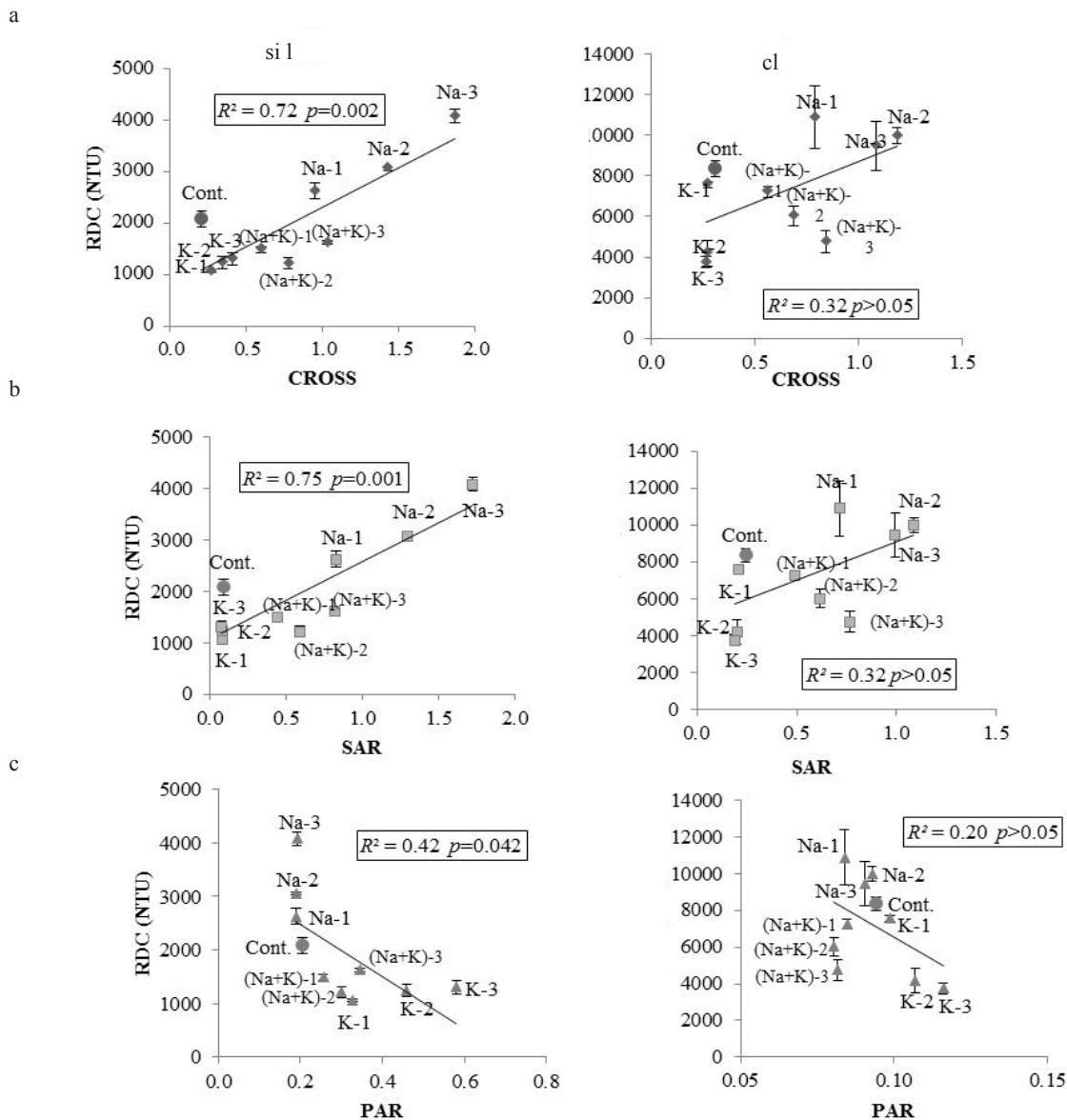


Fig. 2. Amount of readily dispersible clay (RDC) in units of NTU, as a function of the cation ratio of: a – soil structural stability (*CROSS*), b – sodium adsorption ratio (*SAR*), c – potassium adsorption ratio (*PAR*), for the silt loam (left) and the clay soil (right). Labels next to the data points indicate treatments (Table 2), cont. indicates control. Note the different scales for RDC for the two soils.

a function of K for our soils. Moreover, *CROSS* (Eq. (1)) is a measure of the combined impact of Na and K, accounting for the relative dispersive power of Na and K, respectively (Rengasamy and Marchuk, 2011). Similar to *PAR* and *SAR*, negative correlations were found between RDC and *EPP* (Fig. 3a) and positive correlations were obtained between RDC and *ESP* (Fig. 3b). We found stronger relationships (*i.e.* higher R^2 values and lower p values) between RDC and Na concentration, as well as *SAR* and *ESP* than between RDC and K concentration, *PAR* and *EPP*, indicating that the impact on soil structure was stronger for Na than for K. What is more, the relationship between RDC and *CROSS* was similar to that between RDC and *SAR* (*i.e.* similar R^2 values and similar p values), suggesting the dominance of

Na over K in the observed effects. The reason for negative correlations between RDC and *PAR* ($r = -0.65$ and $p = 0.04$ for si l, and $r = -0.45$ and $p = 0.19$ for cl) is probably related to the mineralogy of our soils. The predominant clay mineral was illite (weathered mica) in both soils (Peters, 1969), and K was probably fixed. The impact of K on soil structure in relation to clay mineralogy is discussed in detail below.

The deleterious effect of Na on the soil structure has been reported by several researchers. Levy and Torrento (1995) worked on sandy loam and clayey soils and found that increasing exchangeable Na from 0.5 to 5.5% led to an increase in the amounts of dispersible clay from 22.2 to 30.4%. Dexter and Czyż (2000) reported that when Na is

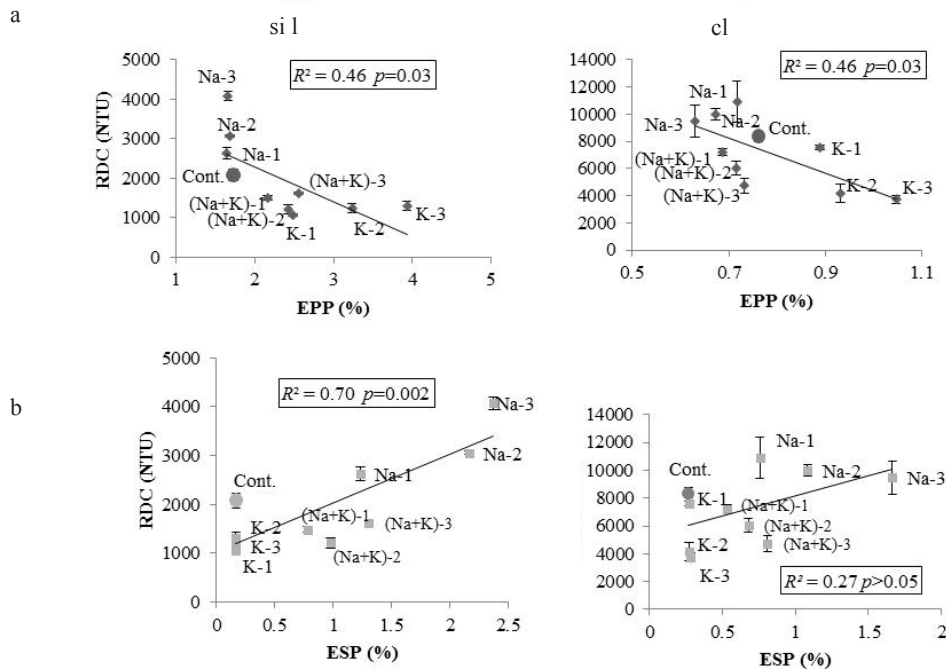


Fig. 3. Amount of readily dispersible clay, RDC in units of NTU, as a function of: a – exchangeable potassium percentage (EPP), and b – exchangeable sodium percentage (ESP) for the silt loam (left) and the clay soil (right). Labels next to the data points indicate treatments (Table 2), cont. indicates control. Note the different scales for RDC for the two soils.

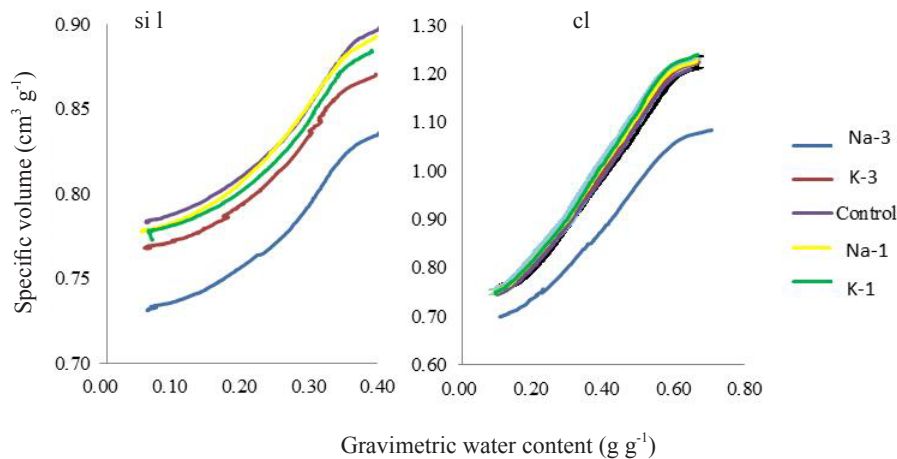


Fig. 4. Shrinkage curves for four treatments (Na-1: minimum Na-concentration; Na-3: maximum Na-concentration; K-1: minimum K concentration; and K-3: maximum K concentration; Table 2) and the controls of si l and cl.

adsorbed on the surfaces of the clay particles, the particles will repel each other due to the creation of extra negative charges on the clay surfaces, and this will result in clay dispersion when the soil is in water.

The relationships between RDC and cationic indicators were different for the two soils (Figs 1-3). The correlations were stronger (higher R^2 value, lower p value) in si l (22% clay) than in cl (45% clay). A possible explanation could be the high cation adsorption due to the higher cation exchange capacity (CEC) of the cl (Marchuk and Rengasamy, 2012).

The shrinkage curves – expressed as specific volume against gravimetric water content – of the soils are shown in Fig. 4. Of note, the clay soil exhibited a steeper shrinkage curve than the si l. A similar observation was made by Schäffer *et al.* (2008), who studied soils with different clay contents. In general, a large slope of the shrinkage curve indicates a weak soil structure (Schäffer *et al.*, 2008). This would explain why RDC was higher in cl than in si l (Figs 1-3).

Little effects of cationic treatment compositions on the shrinkage characteristics, except for the treatment 'Na-3' containing the maximum Na concentration was observed (Table 2) for both soils (Fig. 4). The high Na concentration resulted in a substantial decrease in specific volume corresponding to a decrease in total porosity, presumably due to dispersed clay particles. This effect is similar to that observed by Sou/Dakouré *et al.* (2013), who irrigated different plots of a sandy loam soil from Burkina Faso with tap water and wastewater containing a high concentration of Na, and found that shrinkage curves from irrigated plots with wastewater (high Na concentrations) showed the lowest specific volume due to structural collapse created by the adverse effects of Na on the soil.

The coefficients of linear extensibility (*COLE*) for three matric suction ranges are summarised in Table 3. *COLE* was larger for cl than for si l, which is associated with the higher clay content of cl. Gray and Allbrook (2002) worked on twenty-four soil horizons and series from New Zealand with clay contents in the range of 13 to 86%, and found a significant correlation between *COLE* and clay content in non-allophane samples. Smith *et al.* (1985) studied 66 samples from 32 soil profiles in Israel and obtained a high correlation coefficient between *COLE* and clay content as well.

The lowest values of *COLE* belonged to the 'Na-3' treatment containing the maximum Na concentration (Table 3). The difference in *COLE* between the 'Na-3' and the other treatments was especially pronounced in the cl

soil. These results indicate that the shrinkage capability of soil decreased at high Na concentration due to soil structural collapse caused by clay dispersion.

The water retention curves of the soils are presented in Fig. 5. The clay soil showed higher water retention (higher water content at any given matric suction) than si l due to the higher clay content. The one-month incubation with treatment solutions had generally no or only little effect on water retentions in both soils. The only exception was the treatment with the maximum Na concentration, *i.e.* the 'Na-3' treatment, which increased water retention (Fig. 5). A possible explanation could be that clay dispersion decreased average soil pore size that increased water retention (Fig. 5). This is consistent with the observed reduction in air permeability with increasing RDC (Fig. 6). Our results are further in agreement with the findings of Duy Nang (2012). He studied plant available water on a saline-sodic Australian soil profile as affected by leaching with different solutions and found the highest water retention in the samples with maximum clay dispersion. Duy Nang explained that this was attributable to a shift toward smaller pores because of clay dispersion.

Soil texture, type of cations and concentration of cations in the treatment solutions had significant impacts on k_a . Results of the analysis of variance (ANOVA) for k_a are shown in supplementary Table S1. Since the individual samples had slightly different initial air permeabilities, we calculated the ratio of final (after incubation) to initial k_a (before incubation), $k_{a,\text{final}}/k_{a,\text{initial}}$, as a measure of the change in k_a . The values of $k_{a,\text{final}}/k_{a,\text{initial}}$ were ≥ 1 for all

Table 3. Coefficient of linear extension (*COLE*) for three matric suction ranges for selected treatments (Table 2) and the control

Soil	Treatment type	<i>COLE</i>		
		10-330 hPa	330 hPa – air-dry	10 hPa – air-dry
si l	Na-1	0.70A	0.98A	1.33A
	Na-3	0.66AB	0.93A	1.28AB
	K-1	0.65AB	0.94A	1.27AB
	K-3	0.61B	0.93A	1.25B
	Control	0.74A	0.96A	1.34A
cl	Na-1	1.44A	2.22A	2.64A
	Na-3	1.15B	2.04A	2.37A
	K-1	1.28AB	2.36A	2.68A
	K-3	1.22AB	2.35A	2.65A
	Control	1.37AB	2.23A	2.61A

Values followed by different letters in the same column are significantly different ($p < 0.05$).

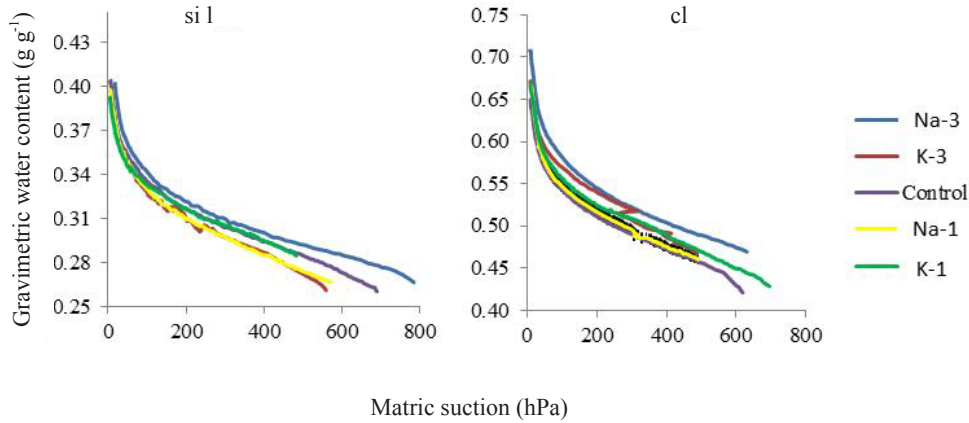


Fig. 5. Water retention curves for four treatments (Na-1: minimum Na-concentration; Na-3: maximum Na-concentration; K-1: minimum K concentration; and K-3: maximum K concentration; Table 2) and the controls of si l and cl.

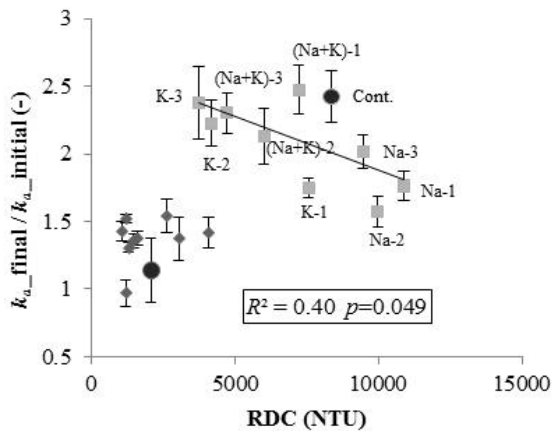


Fig. 6. The ratio of air permeability before incubation to air permeability after incubation, $k_{a_final}/k_{a_initial}$, as a function of the amount of readily dispersible clay (RDC) expressed in units of NTU. si l: rhombi symbols; cl: square symbols. Labels next to the data points indicate treatments (Tables 2 and 3), cont. indicates control.

samples in both soils (Fig. 6), indicating that k_a increased after incubation for all treatments including the control (no treatment solution). This observation is attributed to the effect of moderate drying and wetting on the soil structure. For example, Arthur *et al.* (2012) studied three soils with sandy loam texture from Denmark and found that k_a increased remarkably (from $<2 \mu\text{m}^2$ to $15\text{-}25 \mu\text{m}^2$) with increasing numbers of drying-wetting cycles. They demonstrated that wetting and drying cycles increased soil void ratio, and this had positive effects on k_a .

A significant negative correlation ($r = -0.63$, $p = 0.049$) was found between $k_{a_final}/k_{a_initial}$ and RDC for cl, but not si l. The decrease in $k_{a_final}/k_{a_initial}$ with increasing RDC in cl could be because macropores were filled (*i.e.* clogged) with dispersed clay particles. Arienzo *et al.* (2012) percolated solutions with sodium adsorption ratios (SAR) of 5–40 through an Australian clay loam soil, and observed that relative hydraulic conductivity decreased with increasing

SAR. The fact that we did not find a relationship between $k_{a_final}/k_{a_initial}$ and RDC in si l is probably related to the generally lower values of RDC (Figs 1–3)

The initial k_a was on average larger in si l than in cl, but the ratio of $k_{a_final}/k_{a_initial}$ was lower in si l than in cl, which could be associated to the lower clay content in si l compared with cl. Gregory *et al.* (2009) studied 15 soils from England with clay content from 0.078 to 0.727 g g^{-1} and applied a wetting-drying cycle, including wetting at a matric suction of 5 hPa on a tension table for 24 h, drying at 40°C for 24 h and re-equilibrating at a matric suction of 50 hPa on a tension table. They found that wetting and drying cycles increased the void ratio of the soils only when the clay content was greater than 0.26 g g^{-1} . This could explain why the values of $k_{a_final}/k_{a_initial}$ were found to be larger for the cl (45% clay) than for the si l (22% clay). McNeal *et al.* (1968), in their study of soils with variable clay contents but similar clay mineralogy, also observed that changes of soil structure caused by chemical or environmental factors were greater in soils with higher clay content.

The results with regard to the impact of K on soil structure presented in this paper are apparently in contradiction to the findings presented in Part I of this series of papers (Farahani *et al.*, 2018). Here, we demonstrate that clay dispersion was little affected by K and tended to decrease with increasing K concentration (Fig. 1), while we found that K strongly increased clay dispersion in Part I of our work (Fig. 1 in Farahani *et al.*, 2018). The si l soil used in this paper had a similar texture as the soil used in Part I, and the experimental procedure (the addition of monovalent cations in treatment solutions and incubation for one month) and treatment concentrations (K in the range of 0–60 mmol l^{-1}) were similar in both studies. However, the soils used in this paper were from Switzerland, while the soil used in Part I was an Iranian soil. Although the soils in the two studies had similar clay contents, they had different clay mineralogy. The dominant clay type was mica for both the Swiss and Iranian soils. However, the dominant clay

mineral in the Iranian soil was muscovite (Haghnia, 1982), while illite was the dominant clay mineral in the Swiss soils (Peters, 1969). Below, we will demonstrate that the different impacts of K on soil structure observed in our studies are related to clay-mineral differences in the soils.

Illite has an interlayer K deficiency in comparison with muscovite. Hence, some of the added K ions can be adsorbed between the clay layers of illite, *i.e.* illite can fix K. In contrast, if excess K is added to a soil containing muscovite, the added K ions cannot be adsorbed between the clay layers. Other researchers have demonstrated that hydrous micas and all clay minerals that have been called 'illites' can be fully or partly regenerated to muscovite by the addition and fixation of K ions (Carroll, 1959). The different interactions of muscovite and illite, respectively, with K have implications for the behaviour of clay in soil, and, by extension, for soil structural form and stability.

In our study, we applied K in the range of 0-60 mmol_c l⁻¹, and the results indicated that in the Iranian soil containing muscovite, K ions were not fixed and had a negative effect on soil structure (Part I of this series of papers; Farahani *et al.* 2018), whereas in the Swiss soils containing illite, K ions were fixed, which prevented the negative effects of K on soil structure (this paper). We hypothesise that higher K concentrations have negative effects on soil structure in soils containing illite when the amount of K exceeds the 'K fixing potential' of illite. According to Chen *et al.* (1983), Shainberg *et al.* (1987) and Marchuk *et al.* (2013), the behaviour of K depends on the cation exchange capacity of the minerals and on the concentration of K. In their work, Chen *et al.* (1983) applied 0-1000 mmol_c l⁻¹ K to soils containing a mixture of smectite and illite, and demonstrated that hydraulic conductivity decreased sharply when the applied K concentration was high. Marchuk *et al.* (2013) found that clay dispersion was lower in a soil with minerals (such as smectite and vermiculite) with high exchange capacity (120-150 cmol_c kg⁻¹) that have a fixation affinity for K ions. Hence, for micaceous clay minerals, the negative effect of K on soil structure would decrease in the sequence muscovite > illite > vermiculite. This would indicate that the risk of negative effects from K is highest in unweathered soils. Further studies should be undertaken to test these hypotheses.

CONCLUSIONS

The results obtained the negative effect of Na on soil structure.

1. The amount of readily dispersible clay increased with increasing Na concentration, cation ratio of soil structural and sodium adsorption ratio, suggesting that these are good indicators for assessing the impact of Na on the structure of the studied soils.

2. The treatment with the maximum Na concentration resulted in the highest water retention and in the lowest shrinkage capacity. This effect was associated with high amounts of readily dispersible clay, resulting in a short-range migration of clay and the clogging of soil pores.

3. Air permeability generally increased during incubation due to moderate wetting and drying cycles, but the increase was negatively correlated with readily dispersible clay.

4. Readily dispersible clay decreased with increasing K. It was in contradiction to the findings in Part I, where readily dispersible clay increased with increasing K concentration and K had negative effects on soil structure. We demonstrate that this is attributable to the different clay mineralogy of the studied soils (muscovite in Part I and illite in this paper).

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