Effect of applied potassium concentration on clay dispersion, hydraulic conductivity, pore structure and mineralogy of two contrasting Australian soils

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A B S T R A C T

Re-use of industrial and agricultural wastewater for irrigation can increase the concentration of potassium ions in soil solution and affect soil structural stability. However, investigations of clay dispersion have traditionally focused on soils with high exchangeable sodium. The objective of this study was to quantify the effects of potassium application on physical, chemical and mineralogical properties of two contrasting soils from South Australia. This work combines traditional soil and clay analysis methods with a range of additional techniques, including, scanning electron microscopy, transmission electron microscopy, X-ray diffraction and modeling for characterizing and quantifying the movement of different forms of potassium in soil. In laboratory studies, soils were treated with varying amounts of potassium and the measurements were made on the range of soil/clay properties before and after treatments. The results show that applied potassium can cause dispersion of soil but to a lesser extent than sodium. Potassium cations also could increase soil hydraulic conductivity (HC) to some extent when applied to a soil with high sodium content by substituting the Na^+ on exchange sites. Potassium could be fixed by clay minerals, changing their composition, decreasing cation exchange capacity and increasing mineral potassium content. This increase was confirmed by the decomposition of XRD diagrams and chemical analysis, consistently showing the increases in amount of mica/illite clay minerals in soils treated with potassium rich solutions. The dynamic of "illitisation" can be monitored by XRD analysis both qualitatively and quantitatively. X-ray computed tomography (CT) scanning of the soil columns has allowed visualization and quantification of the changes in pore system occurred due to the application of potassium.

mineralogy

1. Introduction

Wastewaters from urban and agricultural sources have a great potential for re-use in irrigating horticultural and agricultural crops. These wastewaters can have high concentrations of cations such as sodium and potassium and long-term application of such wastewaters may affect the levels of both soluble and exchangeable cations and lead to soil structural deterioration and salt accumulation in soils. Despite the beneficial effects of potassium as a major plant nutrient, it can cause soil clay dispersion in a similar manner to sodium, negatively affecting HC and aggregate stability, the key processes in soil, when interacting with water (Arienzo et al., 2009, 2012; Marchuk et al., 2014; Smiles and Smith, 2004).

Potassium appears to be not as effective as sodium in causing

structural problems in soils (Chen et al., 1983; Levy and van der Watt et al., 1990; Marchuk and Rengasamy, 2011; Rengasamy and Sumner, 1998). Many of the authors have attributed the diverse response of different soils to increases in exchangeable potassium due to differences in soil clay mineralogy (Auerswald et al., 1996; Churchman et al., 1993; amongst many others). In the studies where the effect of potassium was grouped with that of sodium, or intermediate between that of sodium and calcium, the soils were mainly illitic (Churchman et al., 1993) or kaolinitic-illitic (Oster, 2008). These mixed results from the literature point to more research being required to explore the potential effect of applied K^+ on soil dispersive properties and its relationship to clay minerals.

In the present study, we aimed to confirm the effect of increasing level of exchangeable potassium on clay dispersion and HC of soils with contrasting mineralogy. We also examine the changes in soil structure after treatment with different levels of potassium by X-ray computed

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Table 1
Physico-chemical characteristics of used soils.

Soil properties	Units	Soil	
		Red Chromosol[a] Urrbrae series	Black Vertosol[a] Claremont series
pH (1:5 soil/water)		6.7	8.3
EC (1:5 soil/water)	dS/m	0.06	1.03
Total carbon	%	1.5	4.0
Organic carbon	%	1.4	2.2
Carbonate	%	0.2	0.28
SAR		0.23	0.55
CROSS		0.68	1.68
CEC	$cmol_c$/kg	5.8	28.1
Clay content	%	30	56
Dominant Clay Minerals		Illite, Kaolinite[b]	Montmorillonite[b]
Location in South Australia		34˚58'00.41" S 138˚38'03.29" E Waite Research Institute	34˚58'20.64" S 138˚38'11.87" E Waite Research Institute

[a] Australian Soil Classification (Isbell, 1996).
[b] Detailed mineralogical analysis of these soils have been given in Marchuk et al. (2016).

tomography (CT) scanning, X-ray diffraction (XRD) and transmission electron microscopy (TEM). We hypothesize that excess potassium in soil could increase dispersion and decrease HC and that the extent of these changes is modified by the effect that potassium has on clay minerals present.

2. Materials and methods

2.1. Soils used

Two soils were used in this laboratory study, namely Urrbrae Red Chromosol (Rhodoxeralf, US Taxonomy) also locally known as the Urrbrae sandy loam (Hall et al., 2009) and Claremont Black Vertosol (Pellustert, US Taxonomy), classified as self-mulching black cracking clay (Hall et al., 2009). Both the soils are located at the Waite Research Institute, Adelaide, South Australia, Mediterranean climatic zone characterized by hot dry summer and mild short winter, average annual rainfall of 624 mm (Table1). Selection of these soils was based on differences in their clay mineralogy, texture, pH, EC and cation exchange capacity (CEC). Soil samples were collected from the 0.15–0.40 m depth by a hand auger, air-dried, and sieved to 2 mm. Physico-chemical properties, clay mineralogy by X-ray diffraction and locations of the soils are presented in Table 1.

2.2. Soil analysis and measurements

Standard methods were used for the determination of pH and EC (1:5 soil/water), soluble and exchangeable cations (Rayment and Lyons, 2011) and particle size distribution (Gee and Bauder, 1986). Cation Ratio of Structural Stability (CROSS) (Rengasamy and Marchuk, 2011) of the final soil solutions was calculated using the following equations:

$$CROSS\ (mol^{0.5}\,m^{-1.5}) = (Na\ + 0.56\,K)/[(Ca + 0.6\,Mg)/2]^{0.5} \quad (1)$$

where the concentrations of the corresponding ions are expressed in millimole of charge/L.

The sum of exchangeable cations (Ca^{2+}, Mg^{2+}, Na^+ and K^+) is considered as CEC in this report. Spontaneous dispersion was assessed by a modification of the method by Rengasamy (2002) as described in Marchuk (2013). The exchangeable dispersive percentage (EDP)

(Bennett et al., 2016) and the exchangeable sodium percentage (ESP) were calculated as:

$$EDP\ (\%) = [exch\ (Na\ + 0.556\,K + 0.037\,Mg)]/[exch\ (Na + K + Ca + Mg)]\ x\ 100 \quad (2)$$

$$ESP\ (\%) = (Na)/[exch\ (Na + K + Ca + Mg)] \times 100 \quad (3)$$

The zeta potential was measured by laser Doppler velocimetry on a Malvern Zeta Master Particle Electrophoresis Analyzer. The zeta potentials were calculated as the mean of ten runs, each of which was averaged over 25 individual measurements performed automatically by the instrument. The chemical composition of the clay fraction was measured by inductively coupled plasma mass spectrometry (ELAN 6000, Perkin Elmer) after acidic digestion in a microwave oven (Multiwave, 3000 Anton Paar) according the procedure described in Marchuk et al. (2016).

2.3. Hydraulic conductivity experimental procedure

Percolating solutions were prepared using 0.1 M chloride solutions of K^+, Na^+, Ca^{2+} and Mg^{2+} at predetermined concentrations to obtain $CROSS$ treatment solutions ($CROSS_{tr}$) values of 6, 8, 11, 15, but all having the same SAR of 1.2. The concentration of only K^+ was varied to obtain the range of $CROSS_{tr}$ values. The cation concentrations of the treatment solutions are presented in Table 2. Soil samples were evenly packed into Plexiglas columns (6 cm in diameter and 10 cm long) at a bulk density of 1.33 Mg/m³. Both column ends were fitted with nylon mesh screens with a double disk of a gaze mesh on the top of the soil to reduce surface disturbance. Initially the columns were wetted with the treatment solutions to saturation for 24 h from the base by slow capillary rise and then the flow direction was reversed as described in Marchuk (2013). The columns were percolated with three wetting, draining and drying cycles using each of four $CROSS_{tr}$ for each soil. The volume of leachate passing through the columns was monitored. For each cycle, 1 L of one of the $CROSS_{tr}$ solutions was percolated at a constant head of 2 cm and then the soils were allowed to drain and dry for 1 week. Saturated hydraulic conductivity measurements were taken at the end of the last cycle with the deionized water passing through the columns to simulate the infiltration of the soil with rain water.

The experiments were conducted using triplicate samples. To facilitate the visualization of changes in HC with the treatments, we determined the relative HC (Shainberg and Letey, 1984) by assigning the unit (1.0) to the HC measured for the first treatment ($CROSS_{tr}$ 6) for each soil. After HC measurements, the soils from the first and second replicates were removed from the columns, air dried, crushed and passed through a 2-mm sieve. These soils were then analyzed for spontaneous dispersion, zeta potential and other selected properties such as $EC_{1:5}$, $pH_{1:5}$, CROSS of soil solutions ($CROSS_{ss}$) and EDP. To quantify the amount of < 2 µm particles dispersed, measurements were made on a Hach 2100 N Laboratory Turbidimeter at 25 °C and recorded in Nephelometric Turbidity Units (NTU). Turbidity data was transformed to percent dispersed clay [sampled (mg/1000 cm³)/total (mg/1000 cm³)] using the approach of Zhu et al. (2016).

Table 2
Properties of each treatment solution (CROSStr and potassium concentration in CROSStr solutions).

Treatment No	Cations in treatment solutions				TCC	SAR_{tr}	$CROSS_{tr}$
	(mmol_c/L)				(mmol_c/L)	$mol^{0.5}\,m^{-1.5}$	
	K^+	Na^+	Ca^{2+}	Mg^{2+}			
1	20	3.2	5.4	10	38.6	1.2	6.0
2	30	3.2	5.4	10	48.6	1.2	8.4
3	42	3.2	5.4	10	60.6	1.2	11.2
4	60	3.2	5.4	10	78.6	1.2	15.4