Soil & Tillage Research 167 (2017) 61–72

Contents lists available at ScienceDirect

Soil & Tillage Research

journal homepage: www.elsevier.com/locate/still

Differences in loam water retention and shrinkage behavior: Effects of various types and concentrations of salt ions

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ARTICLE INFO

Article history:
Received 6 March 2016
Received in revised form 11 July 2016
Accepted 17 November 2016
Available online xxx

Keywords:
Water retention
Soil shrinkage
Salt ion

ABSTRACT

Soil shrinkage and cracks commonly occur during soil water characteristic curve (SWCC) measurement. These are caused by the capacity of saline soil to retain water, which varies with the type and concentration of salt ions within the soil. A laboratory study was therefore conducted to investigate the effects of four salt cations (K^+, Na^+, Ca^{2+}, and Mg^{2+}) and anions (Cl^-, HCO_3^-, CO_3^{2-}, and SO_4^{2-}) on water retention in loam saturated by salt solutions (5, 30, and 100 g L^{-1}) and on soil shrinkage and cracking during dehydration. The van Genuchten model accurately fit with the SWCCs ($R^2 > 0.99$) obtained. The salt cations generally reduced the soil water-retention capacity, but an extremely low concentration of Na^+ slightly increased it. Increasing salt ionic concentrations gradually reduced the soil water-retention capacity. HCO_3^- and CO_3^{2-} significantly increased water retention, which gradually decreased as the CO_3^{2-} concentration increased. As its concentration increased, Cl^- reduced water retention. An extremely high concentration of SO_4^{2-} (100 g L^{-1}) also reduced water retention. The observed axial shrinkage was synchronous with radial shrinkage in contraction development. For the cations, K^+ and a high concentration of Na^+ facilitated the reduction of soil shrinkage, and axial shrinkage strain (δ_s) was negatively correlated with the K^+ and Na^+ concentrations. Crack length (C_L), crack area (C_A), crack length density (C_{LD}), and crack area density (C_{AD}) all decreased with an increase in the concentrations of K^+, Na^+, and Ca^{2+} but with a reduction in the concentration of Mg^{2+}. For the anions, HCO_3^-, CO_3^{2-}, and a low concentration of Cl^- increased soil shrinkage. Moreover, δ_s was positively correlated with the HCO_3^- and CO_3^{2-} concentrations, and negatively correlated with the Cl^- concentration. The parameters C_L, C_A, C_{LD}, and C_{AD} increased with an increase in the concentrations of HCO_3^-, CO_3^{2-}, and SO_4^{2-} but with a reduction in the concentration of Cl^-. The present results can serve as a theoretical foundation for additional field studies such as the addition of soil additives (e.g., K_2CO_3) to improve soil quality.

1. Introduction

Soil water characteristic curves (SWCCs) define the relationship between soil suction (i.e. pressure head) and the volumetric water content of soil. SWCCs are commonly used to evaluate the size and distribution of soil pores and soil water availability and holding capacity, as well as to estimate the functions of various properties of unsaturated soil and to model the transport of soil water and solutes (Crarrick et al., 2011; Fu et al., 2011; Lu et al., 2004; Mohammadi and Meskini-Vishkaee, 2013; van Genuchten, 1980; Zhou et al., 2014). Many studies have been conducted on SWCC fitting for different soil types (Antinoro et al., 2014; Bayat et al., 2013; Shwetha and Varija, 2015), factors influencing SWCCs (Gao and Shao, 2015; Thyagaraj and Rao, 2010), and effects of soil additives on water retention (Leung et al., 2015; Rawls et al., 2003; Stoof et al., 2010). These studies have largely focused on fresh soil water and non-saline soils. The land area affected by desertification is currently 2.62×10^8 ha, accounting for approximately 27.3% of the total land in China, and is growing at a rate of 2.46×10^5 ha per year. The area of saline-alkaline land, however, is approximately 3.6×10^7 ha (Lv et al., 2009; Yang, 2008), and it may increase gradually in areas with strong evaporation (Xing et al., 2015). Soil salinization and secondary salinization severely

Abbreviations: SWCC, soil water characteristic curve; $C_L/C_A/C_P/C_{LD}/C_{AD}$, crack length/crack area/crack aperture/crack length density/crack area density; TP/TN, treatment saturated by positive/negative salt ion; $T_K/T_{Na}/T_{Ca}/T_{Mg}/T_{Cl}/T_{HCO3}/T_{CO3}/T_{SO4}$, treatment saturated by $K^+/Na^+/Ca^{2+}/Mg^{2+}/Cl^-/HCO_3^-/CO_3^{2-}/SO_4^{2-}$.

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http://dx.doi.org/10.1016/j.still.2016.11.005

damage soil properties in arid and semiarid regions with a shallow groundwater table, substantially reduce crop yields, and exert detrimental effects on ecological environments (He et al., 2014; Ren et al., 2016; Xing et al., 2016). However, soil water is a crucial water resource and is the fundamental for the survival of terrestrial plants. Determining SWCCs for saline soils with different salt solutes to clarify the effects of salt ions on soil water retention is thus imperative.

Field soils tend to swell and shrink when subjected to cycles of wetting and drying, and they also tend to crack during drying (Zhang et al., 2016). Consequently, cracks provide preferential pathways for water infiltration, thus posing adverse effects, because preferential flows through such cracks may lead to reduced soil strength and stability (Li and Zhang, 2010). Sampled soils thus shrink and crack during the collection of data for SWCC construction through centrifugation, which is often ignored. Soil shrinkage negatively affects the growth and development of crop roots, which reduces crop yield (Ren et al., 2016). Soil cracks can modify the geometry of soil pores, further damaging soil structure and changing the transport pathways of soil water and nutrients (Berndt and Coughlan, 1976; Crescimanno and Provenzano, 1999). Furthermore, soil cracks can increase groundwater pollution, as well as waste irrigation water (Beven and Germann, 1982; Ren et al., 2016). Previous studies, such as those by Lima and Grismer (1992) and Pauchard et al. (1999), have investigated the effects of soil salts on cracking but have ignored the effects of salt ions on crack development. Studies evaluating cracking have transitioned from manual measurement procedures to image processing (Liu et al., 2013; Novak, 1999; Peng et al., 2006; Ren et al., 2016; Zhang et al., 2016) such as digital imaging (Kemeny and Post, 2003). Digital imaging has its merits for measuring soil surface cracks because it enables the effective acquisition of cracking parameters without disturbing soil cracks (Li and Zhang, 2010). However, the mentioned studies have ignored soil desiccation cracks when determining SWCCs through the laboratory centrifugal method; specifically, shrinkage and dehydration were divided into two independent components. During dehydration, soils gradually shrink with increasing bulk density and cracking, indicating that changes in soil shrinkage, water content, and bulk density are relatively simultaneous with changes in soil suction. The characteristics of soil shrinkage thus have practical relevance and should be accounted for during SWCC measurements. Few studies, however, have focused on the effects of different salt ions on soil shrinkage and cracking, even though salinity is the main characteristic of saline soils affecting shrinkage. Clarifying the characteristics of shrinkage during soil dehydration can facilitate determining the amount of irrigation required for dehydrated soils. Combining shrinkage with dehydration is therefore of practical relevance.

2. Research objectives

Research into the influence of salt ions on the mechanisms of soil shrinkage and water retention is of theoretical relevance. The main objectives of this study were as follows: (1) to evaluate the effects of various types and concentrations of salt ions on water retention on the basis of SWCCs; (2) to examine the applicability of the van Genuchten (VG) model for SWCC fitting after soils are soaked in saline solutions; (3) to evaluate the effects of various types and concentrations of salt ions on soil shrinkages in axial and radial directions, and on cracking characteristics during dehydration; and (4) to propose an effective soil additive for increasing water retention and reducing desiccation cracking. First, experimental loam samples were collected from a local wheat-corn crop rotation field and saturated with saline solutions of different types and concentrations of salt ions. Subsequently, the centrifugal method was applied to measure SWCCs. The changes in axial and radial shrinkage were quantitatively measured during SWCC construction, and the cracks were then photographed. Finally, a type of soil additive was proposed for increasing water-retention capacity while reducing cracking on the basis of soil-water-retention curves and soil shrinkage properties.

3. Materials and methods

3.1. Experimental materials and design

Experimental soil samples were collected to a depth of 30 cm from a cultivated field in the district of Yangling in Shaanxi Province on the Loess Plateau of China. The soil was loam (based on the USDA Soil Taxonomy System) with a particle size distribution of 17.28% 0–0.002 mm, 44.32% 0.002–0.02 mm, and 38.40% 0.02–2 mm, and it was also a type of vertisols (based on the WRB Soil Taxonomy System) with a primarily montmorillonite mineral content. The liquid limit, plastic limit, and plastic index of the selected loam were 33.0, 17.8, and 15.2%, respectively. The saturated and residual volumetric water contents were 0.4827 and 0.1366 $cm^3\ cm^{-3}$, respectively. The maximum dry density was approximately 1.83 $g\ cm^{-3}$. Four replicates of the samples were air dried (1.27% gravimetric water content), sieved through a 2-mm mesh, and then compacted into cutting rings (100 cm^3; h: 5.1 cm, and d: 5.0 cm) at a bulk density of 1.40 $g\ cm^{-3}$ to simulate the in situ bulk density of 1.40–1.41 $g\ cm^{-3}$.

Seven powder or crystal reagents, namely magnesium chloride ($MgCl_2$), calcium chloride ($CaCl_2$), potassium chloride (KCl), sodium chloride (NaCl), sodium bicarbonate ($NaHCO_3$), sodium carbonate (Na_2CO_3), and sodium sulfate (Na_2SO_4), which all consisted of eight salt ions, were each dissolved in distilled water at concentrations of 5, 30, and 100 $g\ L^{-1}$ according to the rangeability of the total dissolved solids of salt water (3–10 $g\ L^{-1}$), saline water (10–50 $g\ L^{-1}$), and brine water (>50 $g\ L^{-1}$). Distilled water was used as a control treatment (CK). A total of 22 treatments were conducted.

3.2. Experimental method

3.2.1. SWCC construction

All soil samples were saturated in the solutions for 48 h before the trial. Centrifugation (CR21G II, Japan) was used to obtain data for the SWCCs, which were expressed as soil suction s (cm) versus soil water θ ($cm^3\ cm^{-3}$). The soil water was desorbed by applying a high centrifugal force to the pre-saturated soil samples.

All soil samples were dehydrated at speeds corresponding to a specific suction value (Table 1), and after the equilibrium time for a particular s value was reached, the soil samples were removed from the centrifuge to determine the soil water content and the corresponding bulk density. The soil samples were weighed on an

Table 1
Speed of centrifugation and equilibrium time for each tested soil suction condition.

Soil suction (cm)	Speed (rpm)	Equilibrium time (min)
0	–	–
10	310	10
50	693	17
100	981	26
300	1698	42
500	2193	49
700	2594	53
1000	3101	58
3000	5371	73
5000	6934	81
7000	8204	85