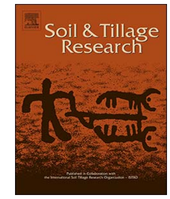
Soil & Tillage Research 177 (2018) 61–67

Contents lists available at ScienceDirect

Soil & Tillage Research

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



Research paper

Effect of static and cyclic loading including spatial variation caused by vertical holes on changes in soil aeration

Xiafei Zhai*, Rainer Horn

Institute of Plant Nutrition and Soil Science, Christian-Albrechts-University zu Kiel, Hermann-Rodewald-Str.2, D-24118 Kiel, Germany

ARTICLE INFO

Keywords:
Soil compaction
Pore function
Gas transport

ABSTRACT

Gas transport properties are important factors influencing soil quality and crop production, as they directly affect respiration processes of plant roots and microorganisms. They depend not only on soil characteristics such as soil texture, matric potential and soil structure, but also on the type of applied stress (i.e. static loading and cyclic loading). Although there are some studies investigating the effects of compaction on soil gas transport properties, experimental data related to spatial variation caused by vertical holes during static loading are scarce. Therefore, the effect of static, following cyclic loading, and the effect of vertical pores during static loading on total porosity, air-filled porosity (ε_a), air permeability (K_a) and relative gas diffusivity (D_s/D_o) at matric potentials of −60 hPa and −300 hPa were investigated by using repacked soil samples with three different textures (sand, silt loam, clay loam). Total porosity and air-filled porosity (ε_a) after static loading and subsequent cyclic loading were lower than before loading. Compaction caused a reduction in total porosity mainly due to the decrease of macropores, which can be derived from the reduced air-filled porosity after compaction. The same was also true for air permeability (K_a) and relative gas diffusivity (D_s/D_o), except for the investigated clay soil at the matric potential of −300 hPa as it was affected by an enhanced soil shrinkage and crack formation. The higher water content and the lower number of macropores of fine-textured soil might be the reason that the silt loam soil at the matric potential of −60 hPa revealed the lowest values of all observed parameters. The effect of artificially drilled continuous and non-tortuous vertical holes in the samples resulted in a slight but insignificant increase in total porosity and air-filled porosity, as they only account for 0.2% of the total bulk soil volume. Because these samples with vertical holes were equilibrated with the major principle stress, they remained rigid during consecutive static loading. Consequently, K_a significantly increased up to more than one order of magnitude, irrespective of the texture and matric potential. Drilling holes caused D_s/D_o to increase by 0.13–14.89 times especially in the fine-textured soil (silt loam) at less negative matric potential (−60 hPa).

1. Introduction

The process of soil aeration is an important determinant of soil productivity. In the unsaturated zone, gas is transported either in the gaseous phase or in dissolved form through the liquid phase. Since the rate of gas transport in the air phase is much greater than in the liquid phase, soil aeration is mostly dependent on the volume fraction of air-filled pores (Hillel, 2003). Soil aeration is restricted when the network of air-filled pores is partially or entirely blocked, when the soil is extremely compacted or when it is excessively wet (Hillel, 2003).

Generally, there are two main mechanisms of gas transport in soils: mass flow or advection/convection and molecular diffusion. Air permeability (K_a) is the governing parameter for mass flow induced by air pressure gradients. Concerning the relative gas diffusivity (D_s/D_o, the ratio of apparent gas diffusion in soil, and gas diffusion in air), we consider it as the governing parameter for molecular diffusion induced by concentration gradients (Glinski et al., 2011).

Gas transport is limited by some resistance factors: (i) Soil texture. It is directly related to soil particle size distribution, and results in different patterns of the water retention curve or pore size distribution, pore continuity and tortuosity, thus influencing air permeability and gas diffusion (Mentges et al., 2016; Deepagoda et al., 2011; Neira et al., 2015). According to Glinski and Stepniewski (1985), the values of air permeability in soils are within the range of 0.01–500*10^{-12} m^2. Clay soil has more fine pores with lower pore continuity, which leads to lower air permeability, whereas air permeability in sandy soil is more dependent on macroporosity and less influenced by pore continuity at a given matric potential (Ball et al., 1981; Mentges et al., 2016). Even though the clay soil and sand soil may have an identical water content, air permeability of clay soil is still orders of magnitude smaller than of

* Corresponding author.
E-mail address: xiafeizhai@gmail.com (X. Zhai).

https://doi.org/10.1016/j.still.2017.11.008
Received 1 June 2017; Received in revised form 16 October 2017; Accepted 10 November 2017
0167-1987/

sand soil (Logsdon et al., 2013). Based on the existing literature, approximate ranges for air permeability in homogeneous soils of different texture range from clay: ≪1 μm^2; to silt: 1–10 μm^2; while fine sand: 10–100 μm^2; coarse sand: 100–1000 μm^2; gravel: ≫ > 1000 μm^2 (Logsdon et al., 2013). (ii) Water content. With the increase of water content, the amount of air-filled pores decreases, which is directly related to pore diameter, continuity and tortuosity, thus affecting soil gas transport (Mentges et al., 2016). (iii) Structure. Air permeability strongly depends on soil structure, especially on the continuity of the active (or functional) air-filled pores. Consequently, it is very sensitive to even small structural changes (Logsdon et al., 2013). If gas diffuses in the continuous, non-tortuous and non-constricted pores and these pores are parallel to the concentration gradient, then relative gas diffusivity equals porosity (Gradwell, 1961). However, since non-continuous, tortuous and constricted air-filled pores, influenced by soil texture, water content and soil structure dominate in soils, relative gas diffusivity is generally smaller than air-filled porosity (Ball, 1981).

Soil compaction increases bulk density and decreases porosity, and the macroporosity in particular (Simojoki et al., 2008; Weisskopf et al., 2010), which affects the geometry and continuity of the pore system. Air permeability and relative gas diffusivity are suitable indicators for identifying soil pore characteristics (Moldrup et al., 2003; Iversen et al., 2001), and for evaluating the changes in soil structure (Fish and Koppi, 1994; Moldrup et al., 2001). Thus, the effects of soil compaction on soil aeration are usually quantified by capacity parameters like air-filled porosity, or by more reliable intensity parameters: air permeability, or relative gas diffusivity (Lipiec and Hatano, 2003). In this study, our objective was to evaluate the effect of differences in soil texture (sand, silt loam, clay loam), matric potential (–60 hPa and −300 hPa) and soil structure (artificially prepared as vertical holes) on soil aeration properties, and to investigate the effect of static and consecutive cyclic loading on gas transport.

2. Materials and methods

2.1. Soil sampling and properties

Disturbed soil samples with different textures were collected from three sites in Germany: (i) The Podsol derived from glacial outwash has sand texture with quite a lot of stones. The experimental agricultural site is located in Schuby (54°52′N, 9°45′E) where the vegetation is annual ryegrass (*Lolium multiflorum*). (ii) The Haplic Luvisol derived from loess has silt loam texture. The arable site was established at the experimental station Klein Altendorf (50°37′N, 6°59′E) in Bonn. (iii) The Stagnosol derived from glacial till is located in Fehmarn (54°27′N, 11°16′E) under arable management. The soil has clay loam texture. The basic soil properties are shown in Table 1. Particle size distribution was determined by the Pipette method after the destruction of organic matter, removal of carbonate, and further bindings by dithionite citrate and pyrophosphate. Soil texture was classified according to USDA classification. pH was determined by the Potentiometric method with soil extractant of 0.01 mol/L $CaCl_2$ solution. $CaCO_3$ content was measured by gas volume method. Organic carbon was determined according to Schlichting et al. (1995).

2.2. Sample preparation

The samples were air-dried, sieved through 2 mm and then repacked with an initial dry bulk density of 1.4 g cm^{-3} in 235 cm^3 soil cylinders (10 cm in diameter and 3 cm in height). The prepared soil cylinders were saturated and then successively drained to matric potentials of −60 hPa on sandboxes and −300 hPa on ceramic plates. The cylinders of clay loam soil at the matric potential of −60 hPa were not prepared, due to the extremely low air-filled porosity which would result in very low values of air permeability and gas diffusivity.

Shrinkage occurred in both silty and clayey samples from saturation to the matric potential of −300 hPa, resulting in the change of initial bulk density and an enhanced preferential air flow along the gaps developing between the soil matrix and the cylinder wall. Therefore, at the matric potential of −300 hPa the cylinders of silt loam and clay loam soils were prepared by another method. The amount of water of silt loam and clay loam soils at the matric potential of −300 hPa was added to the air-dried samples by spraying distilled water to achieve the desired water content and samples were kept in plastic bags for 24 h for water content equilibration. Thereafter, the prepared soil samples were repacked into the cylinders.

2.3. Compaction experiment

The prepared cylinders were compacted under static loading of 50 kPa. The stress was applied for 4 h, followed by an unloading for 1 h. Prior to the loading and thereafter the air permeability and gas diffusivity were determined. Thereafter, these cylinders were compacted under cyclic loading (50 cycles) with a constant external stress of 50 kPa. Each cycle consisted of 30 s of loading and 30 s of unloading. The same soil functionality measurements (air permeability and gas diffusivity) were carried out. Finally, five vertical holes (Ø = 2 mm each) were drilled by a straight core with a diameter of 2 mm in each of these pre-stressed cylinders and they were compacted again under static loading of 50 kPa for 4 h, unloaded for 1 h. Thereafter, the same properties were determined. Each treatment included 5 replicated samples.

2.4. Measurements of air permeability and gas diffusivity

A steady state method was used to determine air permeability. Under a constant air pressure difference of 0.1 kPa across the soil sample, a steady-state air flux was established. The pressure gradient was measured by air flow meter. The air permeability was calculated by the equation based on Darcy's law (Ball et al., 1981):

$$K_a = \frac{qL_s\eta}{A_s\Delta p} \tag{1}$$

where K_a is air permeability (m^2), q is the volumetric flow rate (m^3 s^{-1}), η is the air dynamic viscosity (Pa s), Δp is the pneumatic pressure difference (Pa), L_s (m) and A_s (m^2) are the length of the sample and the cross sectional area of the cylindric sample, respectively.

Gas diffusion coefficient was measured by a double chamber method. The cylinder was installed between two closed chambers, the upper one filled with synthetic air (20.5 ± 0.5% O_2 in N_2) and the

Table 1
Basic physical and chemical soil properties of studied soils.

Sampling site	Depth (cm)	Particle size distribution (%)			Soil texture	pH ($CaCl_2$)	$CaCO_3$ (%)	OM (%)
		Sand 63–2000 μm	Silt 2–63 μm	Clay ≪2 μm				
Schuby	5–20	85.8	10.2	4.0	Sand	5.00	0.07	6.34
Bonn	5–20	10.7	73.1	16.2	Silt loam	7.39	0.21	2.04
Fehmarn	35–55	38.3	25.3	36.4	Clay loam	7.59	13.92	0.72