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Improvement of oxygen transport functions in grave soils due to quicklime application depending on soil texture

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ABSTRACT

Quickliming (application of CaO) was tested as structure amelioration method in order to improve aeration properties in grave soils and thereby prevent decomposition problems due to an insufficient oxygen supply in the burial environment. CaO is expected to promote a stronger aggregation and stabilization in the backfilled soil and thereby enhance pore functionality. In this study, grave simulations (without buried corpses) were set up at three differently textured sites in Germany (S1: sandy loam, S2: silt loam, S3: clay loam texture) with clay contents ranging from 6 to 35%. Each site included two grave simulations: (i) excavation and backfill only ("Nil" treatment) and (ii) addition of 20 kg CaO m^{-3} to the soil backfill ("CaO" treatment) prior to backfilling. Undisturbed soil cores were repeatedly taken at specific time intervals to determine the aeration status in the simulated cover layer (L1, above potential coffin position in 50 cm depth) and the coffin layer (L2, 90–135 cm depth) by measuring the diffusivity and pore functionality parameters (air-filled porosity (θ_a), pore continuity index (C_1) and tortuosity (T)) at field capacity (−6 kPa). Field measurements included a continuous monitoring of field moisture conditions (matric potential) and repeated measurements (2–4 week intervals) of O_2 concentrations in both layers (L1 and L2).

The addition of CaO to the backfill improved the aeration properties in the grave simulations; this was indicated by a higher diffusivity and mostly higher O_2 concentrations at all sites, which was related to a more continuous (C_1) and less tortuous (T) pore system compared to the "Nil" treatment. However, under field conditions, the effectiveness of soil-lime-mixtures was reduced with increasing clay and soil moisture content. A permanently high water saturation in L2 at S2 and S3 offsets the positive effects of CaO on gas transport ability and therefore restricts an undisturbed gas exchange from the atmosphere to the coffin layer. Consequently, for grave soils with high stagnic/ground water level an additional drainage is needed, while for cohesive, clay-enriched soils a more pronounced homogenization and lime mixing intensity is recommended.

1. Introduction

Burials are accompanied by a soil structure disruption through common excavation and backfill practices, which affects the relevant soil functions for gas and water transport in the grave soil. A complete decomposition within the resting times (15 to 25 years) of buried corpses depends on sufficient aeration of the grave soils which requires an almost unimpeded gas circulation between atmosphere, soil cover layer and burial zone underneath (Fiedler and Graw, 2003). Quite in contrast, grave soils on approximatively 1/3 of cemeteries in Germany are afflicted with decomposition problems due to oxygen deficits in the burial (Fiedler et al., 2004b; Pagels et al., 2004). While the formation of indecomposable adipocere (known as "grave wax") is described as a complex and site-specific process (Fründ and Schoenen, 2009), its occurrence is often related to soils with high water levels (Gleysols, Stagnosols) (Fiedler et al., 2004a; Zimmermann et al., 2014) and/or a less conductive pore system in the soil layer above the coffin. However, adipocere formation can also occur under favorable moisture and temperature conditions independent of the soil type (Forbes et al., 2005).

As the most conducting secondary macropores are destroyed during excavation, aeration status and permeability of the backfilled soil depend only on the texture-specific primary pore system. Due to active subsidence and compaction processes, fine-textured soils are likely more susceptible to a loss of pore functionality. In this regard, Quickliming (application of CaO) could be a promising approach to re-improve the pore functionality and therewith, the aeration properties in refilled materials like in grave soils. Zimmermann et al. (2016) conducted field experiments with CaO application to grave simulations on a sandy loam (16% clay) and confirmed the ability of CaO to increase

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the proportion of coarse pores and their stability by a strong aggregation. The use of CaO as stabilization agent is a common technique in civil/geotechnical engineering, especially in clayey soils, in order to improve workability and mechanical stability (Arabi and Wild, 1989; Bell, 1996; Hartge and Ellies, 1977). The stabilization process in lime-soil-mixtures is primarily characterized by the immediate dehydration (exothermic slaking reaction). The resultant adhesive water menisci forces initially stabilize the contact points between soil particles and thereby initiate the formation of aggregates. In the longer term, stabilization can also be reinforced by the enhanced flocculation of clay particles (higher concentration of calcium ions), the development of calcite crusts (after carbonization) between mineral/organic particles, and by secondary cementitious products following the pozzolanic reactions (Al-Mukhtar et al., 2012; Bohne et al., 1985; Maubec et al., 2017). Thus, the overall potential of long-term structure stabilization in soil-lime-mixtures increases with clay content (Bell, 1996; Maubec et al., 2017).

Based on this, our main objective was to determine the effectiveness of CaO application in soil structure stabilization and pore functionality for earthen grave simulations, in soils with varying clay content. We expect that the reconstruction of relevant pore functions, especially for oxygen transport, is more intense the higher the clay content of the backfilled soil and the lower the matric potential at the time of CaO application.

In this applied study, we focus on the effect of CaO application on the aeration properties and transport functions by diffusion, determined under in situ conditions as well as in laboratory studies. In a second step, the results of field and laboratory analyses are combined to determine the dynamic effects of CaO application in the backfilled soil, which represent the variation of in-situ aeration properties under actual field moisture obtained from continuously monitored matric potential data.

2. Material and methods

2.1. Field experiments and soil sampling

The grave simulations consisted of two excavated pits (2 m width × 9 m length × 1.6 m depth) without buried corpses. In one pit, the backfill was mixed with 20 kg m^{-3} granulated quicklime (termed as “CaO” treatment) and in the other pit, the backfill was not mixed with quicklime (termed as “Nil” treatment). For the backfilling process, a generally smaller amount of soil was necessary to refill the excavated grave in the CaO treatment compared to the untreated “Nil” treatment on all three sites, while the amount of soil surplus also depended on the crushing and homogenization intensity of the backfill performed by the excavator shovel. The mixing procedure was performed as homogenously as possible but still in a workable manner for burial practices. However, in soils with higher clay content the homogenization was difficult resulting in larger soil fragments and a less effective intermixture of the soil backfill and the CaO granules.

Disturbed and undisturbed soil samples were taken from two depths: the 50 cm depth (termed as “L1”, and representing the soil layer between the coffin and the atmosphere in an earthen grave) and the 90–135 cm depth (termed as “L2”, and representing the direct surroundings of the coffin). Soil sampling took place before excavation and backfill (reference, “Ref” treatment) and after excavation and backfill at regular time intervals of 3 months from the treatments “CaO” and “Nil”. However, the grave simulations were often waterlogged in fall and winter, sampling was in some cases only feasible during the spring and summer months depending on site conditions. Method-specific differently sized steel cylinders of 100 cm^3 (for pore water characteristics and air capacity) and 471 cm^3 (for diffusivity and air-filled porosity) were randomly taken across a sampling area of ~2 m^2 from the respective depth, selecting different sampling positions within the pits at each of the quarterly samplings.

2.2. Soil sites

The field experiments were set up in 2014 and ended in September 2016 on three differently textured sites in Germany, which are described as follows:

Site 1 (**S1**, **grave soil**) was a cemetery in Northern Germany, where last excavation activities for human burials took place 40 years ago. The soil type is a Terric Anthrosol (Stagnic) according to World Reference Base for Soil Resources (WRB) (2014) with a sandy loam texture (FAO, 2006). Notwithstanding the sand dominated texture, many graves there were affected by decomposition problems. The mean temperature and precipitation sum during the experimental period (year 2015) is 10.6 °C and 622 mm, respectively (DWD WESTE-XL, 2017).

Site 2 (**S2**, **arable soil**) was located at the research field station Klein-Altendorf of the University of Bonn in the North-West of Germany and previously used for crop production. This site is dominated by a silt-loam texture (FAO, 2006) and included two different locations: S2a, a dip (Eutric Stagnosol (Colluvic)), as well as S2b, situated at a more elevated and less wet position in the same field (Haplic Luvisol, derived from loess), where a second experiment was set up in spring 2016. Hence, here the measurement period was reduced to 6 months. Corresponding to its relief position location S2a is exposed to higher (stagnic) water levels in the course of the year in contrast to location S2b. The mean temperature and precipitation sum during the experimental period (year 2015) is 10.7 °C and 650 mm, respectively (Bonn University, 2017).

Site 3 (**S3**, **arable soil**) was situated on island Fehmarn in Northern Germany and previously used as arable land. This site with a (sandy) clay loam texture FAO (2006) and a high clay content > 30% of the calcareous glacial till is exposed to stagnic water (Eutric Stagnosol (Loamic), World Reference Base for Soil Resources (WRB) (2014)) as well as S2a. The decalcification depth was found at 55 cm. The mean temperature and precipitation sum during the experimental period (year 2015) is 10 °C and 675 mm, respectively (DWD WESTE-XL, 2017).

2.3. Field monitoring

2.3.1. Matric potential

Two tensiometers were installed in L1 at the 50 cm depth and in L2 at the 135 cm depth respectively in each treatment (“CaO” and “Nil”), as well as in the surrounding undisturbed soil (“Ref”). Matric potentials (Ψ_m) were recorded hourly via a data logger (DL-102, UGT GmbH, Müncheberg/Germany) over the period of ca. 2 years (2014–2016).

2.3.2. Oxygen concentration

Oxygen concentration was repeatedly measured at different time intervals (2 weeks to monthly) with a portable O_2/CO_2 Gas Analyzer (G100, Geotechnical Instruments, Leamington Spa/United Kingdom). For the measurement, a volume of 200 ml soil air was extracted from permanently installed PVC pipes (Ø = 18 mm, with airtight valves at the upper end and lateral perforations at the bottom). The PVC pipes were vertically installed in the soil in 50 cm and 135 cm depths with two replicates per depth and treatment.

2.4. Laboratory measurements

2.4.1. Gas diffusivity

Effective oxygen diffusion coefficients (D_s) were measured on undisturbed soil cores pre-drained to a standard matric potential of −6 kPa on a sandbox with a hanging water column of −60 cm. A double chamber experiment (Rolston and Moldrup, 2002) was used to monitor the gas exchange through the soil core (Ø = 10 cm, h = 6 cm) which was placed between two gas-tight chambers. The chambers were filled with gases of different oxygen concentration, synthetic air (20% O_2) and nitrogen (0% O_2), respectively. Oxygen microsensors (UNISENSE A/S, Aarhus/Denmark) continuously measured the changes in O_2