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URBAN SOILS AND SEDIMENTS

Soil structure amelioration with quicklime and irrigation experiments in earth graves

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Abstract
Purpose Air supply and soil moisture have significant impact on the decay time necessary for complete decomposition of an interred body. Concerning the general structure and hydraulic as well as pneumatic conditions, in many cases, a permeable refilled soil material surrounded by the undisturbed and less permeable soil outside the grave results in water ponding, less aerated conditions, and lower redox potential values within the grave. This reduces the decomposition speed or even leads to preservation of the entire body.
Materials and methods In order to ascertain soil structural processes and hydraulic properties in an earth grave within the first year after burial, a monitoring of soil redox and matric potentials was realized in newly refilled artificial (empty) graves. We surveyed four variations: undisturbed reference soil, soil backfill in artificial grave, soil backfill in artificial grave amended with 20 kg CaO m^{-3}, and grave base and walls strewed with CaO. In the fourth artificial grave (soil backfill only), irrigation experiments were conducted in order to simulate the effects of grave maintenance on soil water budget. Pore size distribution, air conductivity, and saturated hydraulic conductivity were measured on soil core samples from the variations. The monitoring was realized with redox sensors and tensiometers in 50- and 130-cm depth in all four variations.
Results and discussion Soil structure disruption increased soil porosity but also favored saturation of the soil in context with precipitation events. Compared with the graves without amendment, the addition of quicklime resulted in higher air capacity and air permeability, saturated hydraulic conductivity, and a better-aerated (higher redox potentials) and less water-saturated soil. Non-recurring irrigation with 2.2, 4.4, and 8.9 mm did not affect the soil moisture in the 50- and 130-cm depth. Repeated irrigation with 8.9 mm on consecutive days led to persistent water saturation in the soil, especially in the 130-cm depth.
Conclusions The disturbed soil structure in the cover layer of an earth grave is sensitive to settlement and, together with a tendency to the development of stagnic conditions, this can have negative impact on soil aeration in the grave. Addition of quicklime to the soil enhances crack development in the base and walls of the grave, stabilizes the soil fragments in the backfill, and prevents intensive settlement processes. This reduces water ponding and leads to a better aeration of the soil. Irrigation of earth graves should be reduced to a minimum.

Keywords CaO · Hydraulic properties · Interment · Oxygen supply · Soil structure development

1 Introduction

Notwithstanding an increasing percentage of cremations, interment is still a very common burial practice in Germany. To guarantee fast and complete decomposition of the interred remains, sufficient oxygen supply is imperative. This can only be achieved if the soil is not permanently water saturated and has a well-developed pore system that allows gas transport via convection and diffusion (Zimmermann et al. 2014). Consequently, cemeteries should be established on fairly permeable soils

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without stagnic or gleyic conditions. However, the soil properties were rarely considered when establishing new cemeteries in the past and thus many cemeteries are located on wet and heavy soil with poor aeration. Inquiries by Schmidt (2002) and Pagels et al. (2004) revealed that incomplete decomposition in earth graves occurs in 30–40 % of the cemeteries in Germany because they have unsuitable soils.

Excavation and refill of graves represent a serious interference in soil structure and functionality. Especially in clayey and loamy soils, the more permeable refilled soil material surrounded by the undisturbed and less permeable soil outside the grave often promotes water ponding, less aerated conditions, and lower redox potential values within the grave. These circumstances provoke dysfunctions in the decomposition of the buried remains sometimes even leading to a complete conservation of the body (Ubelaker and Zarenko 2011). Additionally, the risk of water ponding in graves increases if excessive irrigation is realized in the grave maintenance. Studies containing soil physical data from disrupted soils, for example in recultivation areas following open cut mining or civil works, mainly incorporate agricultural utilization with various tillage measures (Kaufmann et al. 2009; Krummelbein et al. 2010; Schaffer et al. 2007). Detailed soil physical investigations in context with earth graves have not yet been conducted. In order to prevent or at least lessen the negative effects of the excavation procedure, the aim must be to support the restoration of soil structure functionality in earth graves.

1.1 Soil structural amelioration with quicklime

Quicklime is routinely used for deep stabilization of soft and clayey soils in order to improve the bearing capacity in association with civil engineering projects (Rodgers 1996; Ahnberg 2004).

Mixing moist, clayey soil with quicklime leads to the following processes (Witt 2002):

1. Lime slaking: an immediate exothermic, water consuming reaction ($CaO + H_2O \rightarrow Ca(OH)_2$). The chemical water consumption (320 g H_2O/kg CaO) supplemented by an elevated evaporation due to the temperature increase dries the soil and thereby already facilitates a beginning soil structure development through shrinkage. In addition, the transformation of 1 kg CaO to 1.32 kg $Ca(OH)_2$ leads to an increase in dry matter (Scholz-Solbach 2004).
2. Gel stage (hydration): silicates und aluminates are dissolved and create new gel-like hydrate phases with calcium in the pore spaces.
3. Neolithic stage (pozzolanic reactions): the gel crystallizes and leads to a cementation of the soil particles. The pozzolanic reactions continue 1–5 years, depending on soil conditions.
4. Carbonatization: the slaked lime reacts with CO_2 and forms carbonates.

The transitions between the listed processes are fluent. The advantage of quicklime for application in the context of excavation and refill procedures is the fast and strong first reaction of slaking, which enables a beginning stabilization of the excavated soil fragments already with the first contact between quicklime and soil. In the medium term, quicklime application to soil has the same effect as the application of slaked lime, calcite, or dolomite lime: it enduringly raises the soil pH (Beckie and Ukrainetz 1996; Curtin and Smillie 1986; Moore et al. 2012), boosts microbial activity and the decomposition of organic matter (Jaskulska et al. 2014; Macdonald 1979; Muller and Berg 1988), and delivers calcium cations to the soil, which stimulate the development of cationic bridges between organic matter and clay and thereby help to stabilize organic matter in soil aggregates (Briedis et al. 2012). Furthermore, the added calcium promotes flocculation of clay particles as it causes a compression of the electrical double layer and thereby allows the approach of particles (Fiedler and Bergmann 1955; Haynes and Naidu 1998). The subsequent cementation processes between soil particles increase the mechanical stability of soil aggregates (Hartge 1977; Chaplain et al. 2011), the shear strength (Beese et al. 1979; Rajasekaran and Rao 2002; Cheng et al. 2013), and the rigidity of the pore systems and thus the permeability (Rajasekaran and Rao 2002; Cheng et al. 2013). Compressibility is reduced (Beese et al. 1979; Cuisinier et al. 2011) and existing functional structures are preserved. Lime decreases plasticity and swell potential of clayey soils (Al-Mukhtar et al. 2012), so the structural weaknesses of these soils can be attenuated (Scheffer et al. 1963). However, liming does not reduce the shrinkage potential (Stoltz et al. 2012) and consequently, the formation of aggregates through shrinkage processes is not limited.

The mentioned qualities raised the idea to investigate the application of quicklime to soil backfill for soil structure amelioration in context with burial procedures, because the better the initial situation after the burial as the starting point for the decomposition can be defined, the more reliable can the predictions of the following processes within the next months, years, and decades be. We hypothesize that quicklime application improves the soil functionality with regard to gas and water transport fast and enduringly and thus helps to guarantee complete decomposition of the buried bodies. The latter is however not subject of the paper.

2 Materials and methods

2.1 Field measurements and sampling

In order to investigate the soil physical processes in earth graves within the highly sensitive time span just after burial in spite of ethical concerns, we established a field experiment with artificial (empty) graves. The experimental site was a research farm in northern Germany. Soil type was a stagnic Luvisol, developed from young moraine glacial loam (soil properties in 50-cm depth 51 % sand, 33 % silt, 16 % clay, $pH_{(CaCl2)}$ 6.5, 0.2 mass% organic carbon).

Three graves were excavated 150 cm deep, 150 cm wide, and 300 cm long (Fig. 1). In variation A, the soil was only excavated and filled back. In variation B, the soil backfill was mixed with 20 kg CaO m^{-3} (granulated, particle size 0–6 mm). Additionally, the base and the walls of the pit were strewed with quicklime in order to promote crack formation through shrinkage and thereby facilitate gas and liquid exchange between the soil backfill and the surrounding soil. Variation C resembles variation A and was used for irrigation experiments in order to survey the impact of the watering of the grave planting on soil water regime in earth graves.

In each grave and in the undisturbed reference soil, we installed tensiometers and redox sensors in 50- and 130-cm depths, each with two replications (Fig. 1b). The depth of 50 cm represents the cover layer above the coffin, while the depth of 130 cm represents the decomposition zone (coffin and surrounding disturbed soil) in an earth grave. Matric and redox potentials were continuously measured in minute cycle, mean, max, and min values were logged half-hourly. Redox potentials were measured with platinum electrodes and a silver-silver chloride reference electrode positioned in a groundwater well next to the observation plots. Each grave includes an area of 150 m^2 for soil sampling during the still ongoing monitoring without disturbing the sensors. In order to survey soil structure development, undisturbed soil cores (98 cm^3 cylinders) were taken from the reference soil when installing the graves and from variations A and B 60 and 195 days after backfill. In order to highlight the medium- to long-term effects of backfill and quicklime application on soil structure in the cover layer of an earth grave, we present the soil physical results of the samples taken from the 50-cm depth, 195 days after backfill.

2.2 Calculation of water levels

In a saturated soil, tensiometers are able to work just like piezometers as they measure the pressure of the hydrostatic head above the ceramic cup. This pressure was related to the installation depth of the tensiometer in order to estimate the upper fringe of the water-saturated soil zone and thereby achieve information about the extent of water ponding in the graves.

2.3 Laboratory measurements

Saturated hydraulic conductivity, bulk density, and pore size distribution derived from the water retention functions were measured on undisturbed soil cores according to Hartge et al. (2016). Water content was calculated from matric potentials in accordance with the van Genuchten parameters α, n, and m (Van Genuchten 1980, van Genuchten et al. 1991), which were determined by fitting the retention curve to the measured water contents of the undisturbed soil samples at pF 1.5, 1.8, 2.2, 2.5, 2.7, and 4.2, respectively, using the program RETC version 6.02 (van Genuchten et al. 2005).

2.4 Statistics

Air capacity, air permeability, and saturated hydraulic conductivity data were tested for significant differences with the Mann-Whitney U test (Mann 1947) as the datasets were not normally distributed. Matric and redox potentials are measured once per minute and logged as arithmetic means once

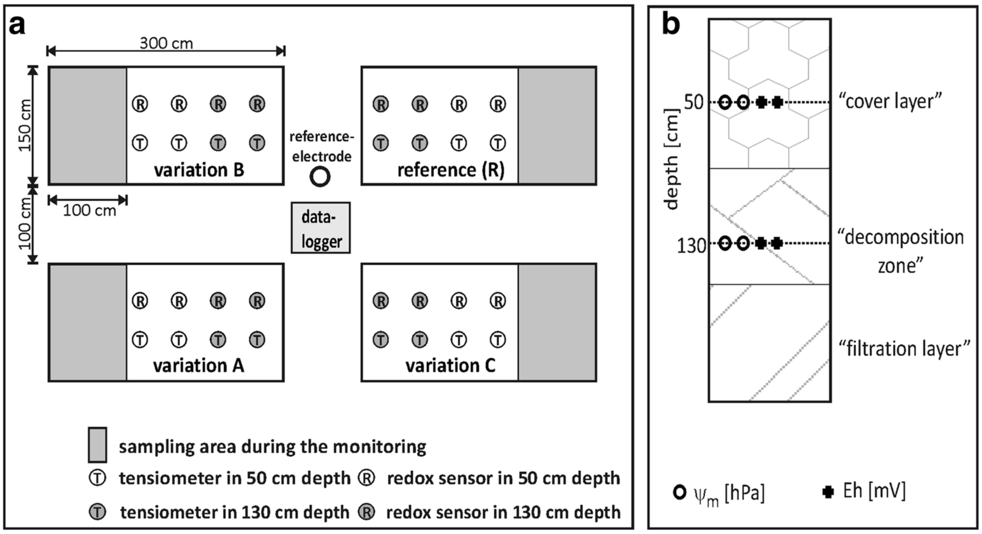

Fig. 1 **a** Experimental setting with arrangement of the reference plot (undisturbed soil), variation A (backfill only), variation B (backfill amended with 20 kg CaO $\mathbf{m^{-3}}$), and variation C (backfill and irrigation); **b** vertical distribution of the tensiometers (ψ_m) and redox sensors (Eh) and allocation to the functional zones of an earth grave

per hour for each sensor. The shown data are arithmetic means of two sensors per depth and variation, respectively.

3 Results

3.1 Air capacity, air conductivity, and saturated hydraulic conductivity

Excavation and refill of the soil led to a significant increase in air capacity in variations A and B compared to the undisturbed reference soil (Fig. 2a). Consequently, also air conductivity at field capacity (Fir. 2b) and saturated hydraulic conductivity (Fig. 2c) were elevated in variations A and B. Air capacity, air conductivity, and saturated hydraulic conductivity are higher in variation B than in variation A.

3.2 Water retention

Excavation and backfill leads to an increase in total porosity and thus to higher volumetric water contents near saturation in variation A (Fig. 3). Even though total porosity is not elevated in variation B, the application of quicklime has caused a shift in pore size distribution. This is visible in the steeper slope of the water retention curve in variation B compared with the reference soil, leading to remarkably lower water contents between pF 1.8 and pF 4.2. Consequently, the soil in variation B will contain less water and thus more air at a given matric potential than variation A.

3.3 Instant effects of backfill and quicklime application on soil matric potentials

Mixing the soil backfill with 20 kg CaO m^{-3} (variation B) led to a desiccation of the nearly water-saturated soil (see reference) to −150 hPa in the 50-cm depth directly after the application (Fig. 4). But, also the excavation and backfill alone (variation A) led to a slight decrease in matric potential down to −50 hPa, however, followed by a pronounced increase to positive values (saturation) as a result of a precipitation event on September 14. From day 3 after backfill, matric potentials in variation B resemble matric potentials in reference soil, while matric potentials in variation A remain visibly higher in the 50- and 130-cm depths, respectively.

3.4 Subsoil ponding

Subsoil ponding occurs in all variations as already the undisturbed soil shows stagnic conditions. Soil structure disruption increases the duration of the water-saturated periods and the extent of the water-saturated zone in the soil profiles (Fig. 5, variation A). Precipitation events in May and June 2012 cause short periods of water ponding in variation A, while the reference soil and variation B are not affected. Water ponding in variation B is in any case less pronounced than in variation A and often even less pronounced than in reference soil. In the hydrological year 2012, positive average matric potentials (arithmetic mean of 1440 measurements in 24 h respectively) were measured on 303 days in reference soil, on 315 days in variation A, and on 226 days in variation B.

3.5 Redox potentials

In spite of high soil water contents, redox potentials in the reference soil are mainly oxic with only short periods of anoxic conditions (Fig. 6). Due to water ponding, variation A shows strongly reducing conditions in the 130-cm depth.

3.6 Impact of grave irrigation on soil water regime

The experimental setting in variation C corresponds with variation A. Four different irrigation experiments were conducted in variation C. The amount of water was chosen accordingly with realistic irrigation events in cemetery practice. The following irrigation events were performed (Table 1):

The reactions of soil matric potentials on the irrigation events are shown in Fig. 7. Only the repeated irrigation with an 8.9-mm water (Fig. 7, irrigation event IV) leads to a pronounced rise in matric potential in the 50- and 130-cm depths. Just like the single irrigation event III, first irrigation with

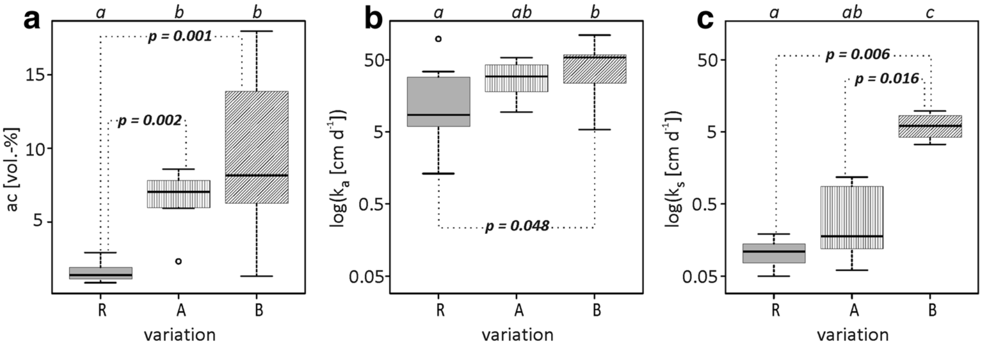

Fig. 2 Air capacity (ac), air conductivity at field capacity (k_a), and saturated hydraulic conductivity (k_s) in the 50-cm depth in reference (R, undisturbed soil) and variations A (backfill only) and B (backfill amended with 20 kg CaO m^{-3}) 195 days after backfill, *italic letters* indicate significant differences, $n = 5$

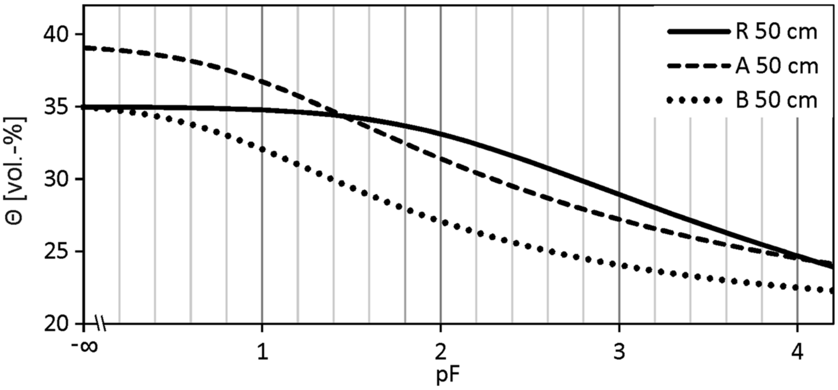

Fig. 3 Fitted water retention curve for reference (R, undisturbed soil) and variations A (backfill only) and B (backfill amended with 20 kg CaO m^{-3}) 195 days after backfill in the 50-cm depth

8.9 mm did not cause any measurable reaction of the matric potentials in irrigation event IV. The second irrigation with 8.9 mm 25 h later caused a rise in matric potential of 6 hPa in the 50-cm depth and 30 hPa in the 130-cm depth. In the 130-cm depth, the soil is water saturated after this irrigation event. After the third irrigation with 8.9 mm, the soil is water saturated in the 50- and 130-cm depths. Although matric potentials in the 50-cm depth begin to decline right after the third irrigation event, the soil remains water saturated for the subsequent 50 h. Then, a precipitation event prevents further desiccation.

4 Discussion

Soil structure disruption, homogenization, and the following compaction through settlement processes can severely deteriorate pore continuity and functionality and disturb the transport of both gas and liquid (Schjonning et al. 1999; Kuncoro et al. 2014). The reduced gas transport can slow down or even prevent decomposition in earth graves due to lack of oxygen (Forbes et al. 2005). This effect is even more severe if the surrounding soil does not allow a sufficient drainage of the pit and water ponding occurs. Accordingly, the low redox potentials in variation A document the poor oxygen supply in the often water-saturated base of the grave.

The characteristics of the soil structure in the backfill, especially with regard to the ratio of pores that can still contribute to gas transport processes, are steered mainly by the persistence of the existing aggregate fragments in the backfill and are thus a function of the aggregate stability in the undisturbed soil before the excavation/backfill procedure. Factors that control aggregate stability in this context are, besides aggregate dry density (Horn and Dexter 1989), number, duration and intensity of shrinkage and swelling cycles (Horn 1990), content and type of organic matter (Piccolo and Mbagwu 1999; Annabi et al. 2011), and carbonate content (Chan and Heenan 1999), particularly the silt and clay content (Mamedov et al. 2007; Kodesova et al. 2009) and the ψ_m (Francis and Cruse 1983; Baumgartl and Horn 1991). Especially in moist soil, the aggregate stability is often too low to resist the mechanical forces emerging from the backfilling procedure, especially if the backfill is additionally compressed with the excavator shovel (Duncan and Bransden 1986). In the subsequent period, precipitation events promote settlement processes that often include further aggregate breakdown. The resulting plastic deformation and aggregate coalescence leads to a gradual homogenization of the soil matrix and, consequently, to a reduction in pore volume and connectivity and an increase in bulk density (Ghezzehei and Or 2000).

Soil structure and aggregate stabilization via the application of quicklime to the soil backfill reduces homogenization

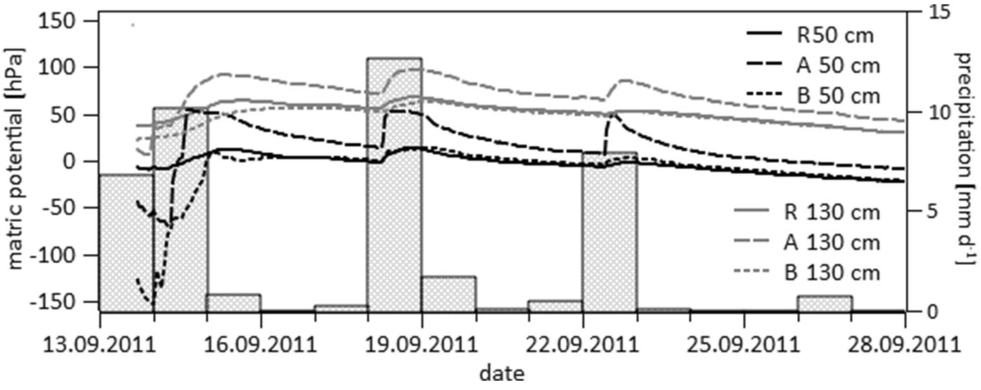

Fig. 4 Matric potentials in reference (R, *straight lines*, undisturbed soil) and variations A (*dashed lines*, backfill only) and B (*dotted lines*, backfill amended with 20 kg CaO $\mathbf{m}^{-3}$), 50-cm (*black lines*) and 130-cm (*gray lines*) depth, and precipitation (*shaded bars*), days 1–14 after excavation, September 2011

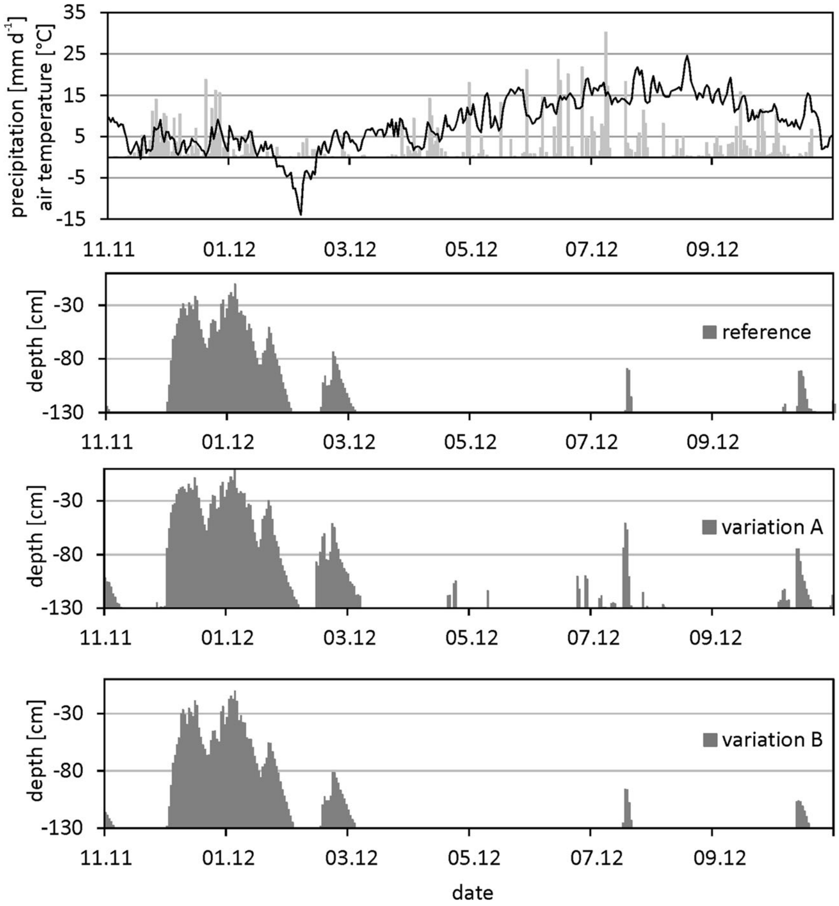

Fig. 5 Precipitation (*light gray bars*) and air temperature (*black line*) at the survey site, extent of the water-saturated soil zone in reference (undisturbed soil), variation A (backfill only), and variation B (backfill amended with 20 kg CaO m^{-3}), hydrological year 2012 (days 50–416 after excavation)

and settlement processes in the subsequent period and thereby helps to maintain soil functionality and prevent severe undersupply with oxygen in the subsoil. Hartge (1976), (1977) determined a better conservation of the original coarsely porous, aggregated condition in drainage ditch backfill (30–40 % clay) enriched with quicklime. Accordingly, the results in this paper show that mixing the excavated loamy soil with 20 kg CaO m^{-3} during the backfill and strewing the base and walls of the

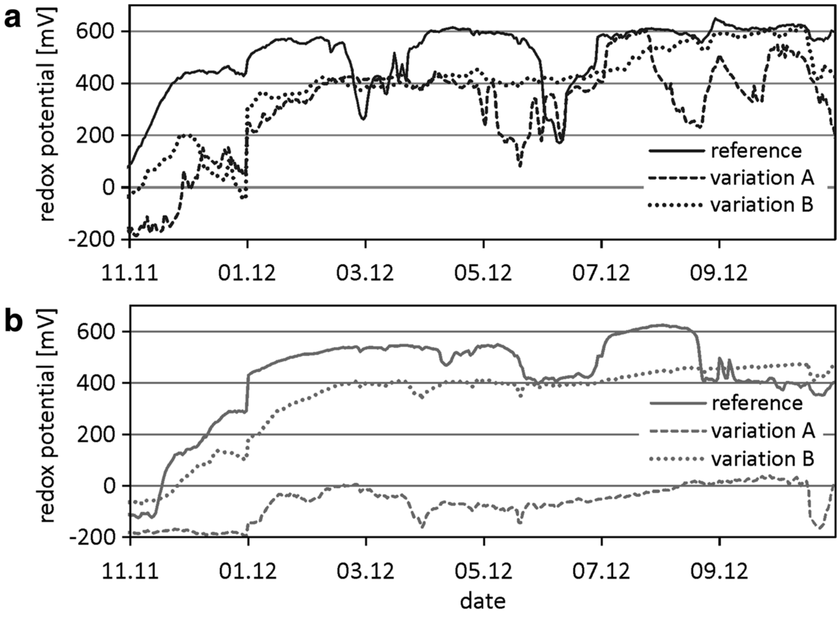

Fig. 6 Redox potentials in reference (undisturbed soil) and variations A (backfill only) and B (backfill amended with 20 kg CaO m^{-3}), **a** 50-cm depth and **b** 130-cm depth, hydrological year 2012 (days 50–416 after excavation)

Table 1 Variations of irrigation experiments

Irrigation event	Irrigation amount (mm)	Corresponding irrigation on single grave (2 m^2) (count of 10 l ewers)	Irrigation days in a row
I	2.2	0.5	1
II	4.4	1	1
III	8.9	2	1
IV	8.9	2	3

pit with CaO (variation B) led to better pore functionality with respect to air and water conductivity, reduced water ponding, faster drainage and desiccation (especially in the 50-cm depth), and higher redox potentials compared with variation A (without CaO) during the complete measurement period. In more than 50 % of the hourly logged measurements, the soil in variation B even exposed more negative matric potentials than the undisturbed reference soil. Also, Ellies et al. (1978) documented a faster near-surface desiccation in soil columns enriched with 5 % quicklime compared with quicklime-free soil columns. The results prove that the amelioration of soil structure functionality that is achieved through the application of quicklime to the soil backfill together with the improved connection between the soil backfill and the surrounding soil leads to higher redox potentials and consequently better oxygen supply in the soil and thus optimizes the conditions for fast and complete decay in earth graves.

Irrigation, as it is practiced in connection with the grave maintenance, affects the soil water regime in an earth grave and can favor incomplete decay or preservation of the body (Horn and Fleige 2001; Pagels et al. 2004). So far, there is no scientific data on the annual amount of irrigation on cemeteries. The individual amount of irrigation for each single grave can already vary considerably within a grave field depending on the individual maintenance intensity. Estimations for irrigation amounts reach from 50 to 1000 mm a^{-1} (Blume 1981; Fleige et al. 2002; Weinzierl and Waldmann 2002; Wourtsakis 2002), representing 10–200 irrigations with 10 l a^{-1} grave^{-1} (grave surface 2 m^2). Especially in the summer months, daily irrigation amounts of 5–10 mm (one to two 10-l ewers per grave) are very common. The performed irrigation experiments revealed that single irrigation events of 2.2, 4.4, and 8.9 mm do not cause a rise in matric potential in the 50- and 130-cm depths in the surveyed glacial loam. Clearly more distinctive is the effect of cumulative irrigations within a short time span. With three irrigations of 8.9 mm respectively within 38 h, soil matric potential rose toward water saturation in the 50- and 130-cm depths already after the second irrigation event. Hence, occasional irrigation of earth graves in accordance with plant water uptake does not have negative effects on soil aeration in a loamy soil, as the wetting front does not advance far into the soil and the water is consumed by the vegetation. However, repeated (daily) irrigation can gradually saturate the cover layer. Besides blocking the gas transport through the pores, high water contents also increases water

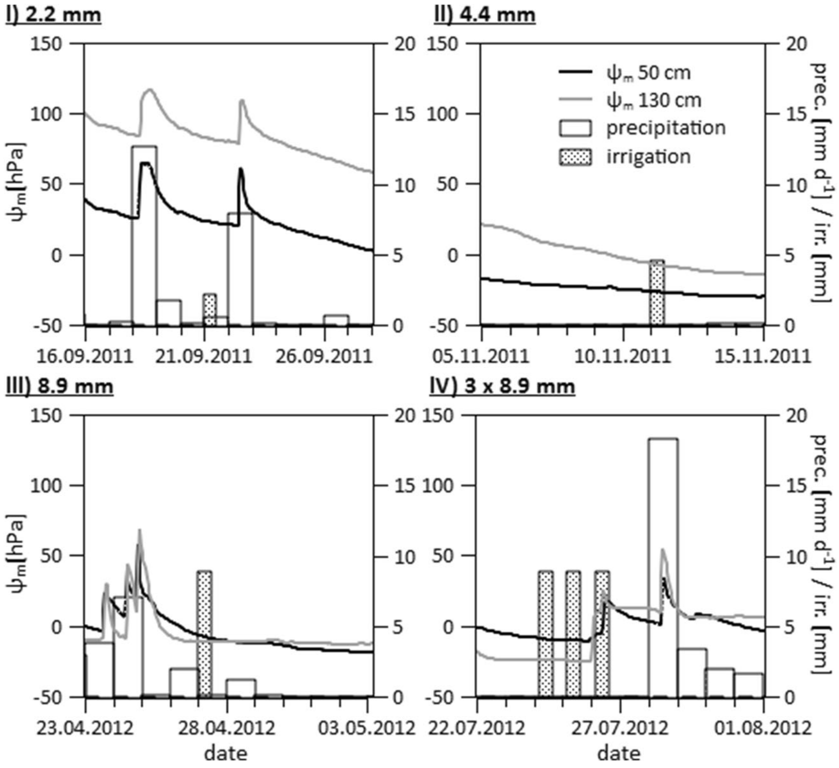

Fig. 7 Variation C (backfill and irrigation), matric potentials in the 50- and 130-cm depths, precipitation and irrigation with 2.2 (I), 4.4 (II), 8.9 mm (III), respectively, 3 days on a row (IV)

conductivity and thereby favor water transport toward the coffin, which again provokes water ponding in the grave.

5 Conclusions

- An elevated saturated hydraulic conductivity in the soil backfill compared with the surrounding undisturbed soil can favor water ponding in the grave. In this case, air supply in graves is limited rather by water-blocked pores than by a reduction of soil structural functionality.
- Addition of quicklime to the soil leads to the development of a rather loose and coarse soil structure and enhances crack development in the grave base and walls. This reduces the ponding and leads to a better aeration of the soil.
- Irrigation of earth graves should be reduced to a minimum, in order to keep soil water content low and thereby facilitate gas transport processes.

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