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Effect of aging on the physical properties of landfill cover layers

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Abstract

Physical properties of soil material are essential criteria for the suitability of material to be used as cover layers or water retaining (ET) layers of landfills. Important parameters, such as available water capacity and saturated hydraulic conductivity, are usually derived from easily measurable properties (such as soil texture) with the help of tables, or are measured on artificially compacted samples in the laboratory. Both methods do not consider structural changes taking place mainly in the first years after installation. Key factors for the development of the soil structure are freeze-thaw cycles, swelling and shrinkage due to moistening and drying, and the influence of root growth. The investigation was carried out with dredged material (river sediments) which was planned to be used for a landfill cover layer. Freeze-thaw cycles were simulated for a few days each in a laboratory freezer; swelling and shrinkage was simulated by alternating between water saturation and complete drying in a drying oven. The vegetation experiment was carried out in the open on a site filled with 20 cm dredged material. The effects of the environmental factors result in a modification of the pore system. All variants showed a significant increase in air capacity and a significant decrease of the available water capacity at constant total pore volume. With respect to the suitability of the material for landfill cover layers, the results imply that that the legally specified minimum values for available water capacity should be rather increased due to a possible decrease over time. However, the average decline of the available water capacity of 6%v/v with time due to aging, and the assumed penetration depths of the aging processes in the upper third of the cover layer, would result in a rather small increase of a few decimeters in layer thickness necessary to achieve the water storage targets. More important seems the increase in air capacity due to aging processes, which is of considerable importance for the growth of plants especially in the upper part of the cover layer. The risk of too high soil density associated with too low air capacity for optimum plant growth, thus, is somewhat reduced due to the increasing air capacity with aging.

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Introduction

Physical properties are essential criteria for the suitability of soil material to be used as conventional cover layers or water retaining layers (ET cover systems) of landfills. ET cover systems are designed to minimize percolation. These cover systems rely on the property of soil to store water until it is transpired through vegetation or evaporated from the soil surface. Important parameters are the available water capacity (AWC) as a measure of water storage, the air capacity (AC) as an important parameter for plant growth and the saturated hydraulic conductivity as a significant factor determining the leaching behavior of water.

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Specifications for physical properties of soil material to be used as landfill covers can be found in different sets of rules and regulations in Germany. The „Ordinance on landfills and long-term deposits" (DEPV, 2009) gives details of the requirements for a cover layer: It must have an AWC of at least 140 mm for the total cover layer. If the cover layer is designed as an ET cover system, the AWC must be at least 220 mm, and the seepage water per year may not exceed 60 mm. A minimum of 8 %v/v throughout the cover layer is recommended for the AC (GDA, 2006).

A simulation of the water balance of cover layers or their individual components to optimize different variants is often done with computer models, e.g. with the commonly used Hydrologic Evaluation of Landfill Performance (HELP) software (Berger and Schroeder, 2011). Crucial and necessary input for such a model is the field capacity (FC), the AWC and the saturated hydraulic conductivity (Ks) of the components. Thus, the physical properties of cover layer material are important parameters to evaluate its usability for a cover layer. The physical properties are mostly derived from tables (which were usually developed based on experiences with undisturbed mineral soils and are therefore only very limited suitable for the characterization of cover layer material) or they are measured on samples artificially compacted in the laboratory. Both methods do not consider the alterations taking place due to aging mainly in the first years after the installation of the material.

Several studies on the structural development and, thus, on changes and restructuring of the pore system and its physical properties exist. However, nearly all were performed on natural mineral soils, mostly under agricultural land use and for long periods (several decades). Soil material (clay, loam) changes its structure through natural soil development which includes the mechanical action of freezing and thawing, swelling and shrinkage, cryoturbation and root growth (Blume et al., 2010). These processes usually increase the coarse pore fraction, which can be explained by aggregation, displacement and rounding of aggregates (Blume et al., 2010). For longer time periods also the colonization with soil organisms is an important factor for the soil structural development.

Aim of the present study is to determine the effect of freeze-thaw-cycles, swelling/shrinkage and root growth on the structural development of landfill cover layers consisting of dredged material.

Material and Methods

For the simulation of substrate aging material from a landfill site for dredged material of the ports of the city of Bremen was used. Dredging is a fundamental activity for most ports. It consists of the excavation of material from the river bed mainly to maintain or improve navigable water depths. The dredged sediments are dewatered and stabilized in dewatering fields within 1 year. After the dewatering process, the material is deposited in a landfill.

The texture of the dredged material is silty loam with 27 %w/wclay, 58 %w/w silt and 15 %w/w sand. The $CaCO_3$ content is 6.5 %w/w, the organic matter content 5.6 %w/w. The material density is 2.71 g/cm^3. The freshly installed dredged material has a low saturated hydraulic conductivity and high water storage capabilities (Nagel, 2011). At higher bulk densities low air capacity and low hydraulic conductivity was found (Nagel, 2011). These properties principally allow the use of dredged material for landfill cover layers, but the suitability of the freshly installed material is limited particularly by the low air capacity (Nagel, 2011). Possible additional pollutant problems are not further discussed here.

For the artificial aging experiments of the dredged material experimental plastic containers with the dimensions 40 x 30 x 10 cm were used in which the dredged material was installed with a height of 8 cm and a defined bulk density (total material volume 9.6 L).

In order to assess the dredged material under standardized conditions it must be installed with a previously defined bulk density. The bulk density of the dredged material for the test containers was determined prior to the main measurements: The dredged material with the current water content was installed in the test containers and compacted with punch and a 2.0 kg hammer. Subsequently, the bulk density was determined according to DIN ISO 11272 (DIN ISO 11272:1998, 2001). The maximum attainable bulk density was 1.07 g/cm^3. For the experiments 90 % of the maximum bulk density was used, i.e. a bulk density of 0.96 g/cm^3. Similar values have been measured before for landfill cover layers from the same dredged material (Nagel, 2011). The cause of the relatively low bulk density is the high water content during installation, which is 40-50 %v/v even in mature dredged material in comparison to a water content of about 35 %v/v which is optimal for the compaction of a silt loam. This high water content is typical for the condition in which the mature dredged material is used.

Before starting the experiments undisturbed soil core samples were taken from the experimental containers.

Freeze-Thaw-Cycle

To simulate the effect of freezing and thawing of the dredged material, the material was installed into the test containers at the current water content (approximately 49 %v/v, slightly drier than field capacity). The test containers were then sealed with plastic wrap and closed with a lid ensuring that the water content remained constant. The simulation of the freeze-thaw cycle was performed by a freezing phase of 24 h at -17 °C and a thawing phase of 72 h at +7 °C. A freezing phase with subsequent thawing phase forms a freeze-thaw cycle. Figure 1 schematically shows the experimental procedure as well as the change in volume of water in its solid and liquid state. For the experiment six containers each were scheduled for 7 and 14 cycles. After 7 and 14 cycles 4 undisturbed soil cores were taken from each test container (a total of 24 sample rings each). Of these, 6 were used for the measurement of water retention parameters and 18 to measure the saturated hydraulic conductivity.

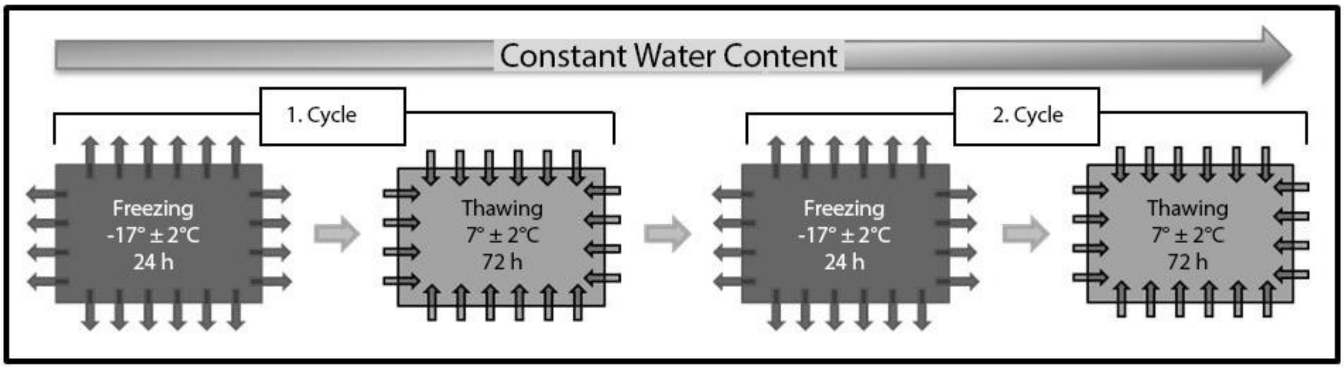

Figure 1. Experimental procedure of two freeze-thaw-cycles at constant water content

Swelling and Shrinkage

The process of swelling and shrinkage was simulated by saturating the installed dredged material and subsequent drying at 32 ± 3 °C (Mischra et al., 2007). For this purpose, the samples were saturated for 72 h in the swelling phase. Subsequently, the samples were dried in a thermostatically controlled and ventilated oven at 32 ± 3 °C (shrinking phase). Figure 2 schematically shows the experimental procedure of two test cycles as well as the volume change due to swelling (volume increase) and shrinkage (volume decrease) of the swellable clay fraction. For the experiment six containers each were scheduled for 7 and 14 cycles. After 7 and 14 cycles 4 undisturbed soil cores were taken from each test container (a total of 24 sample rings each). Of these, 6 were used for the measurement of water retention parameters and 18 to measure the saturated hydraulic conductivity.

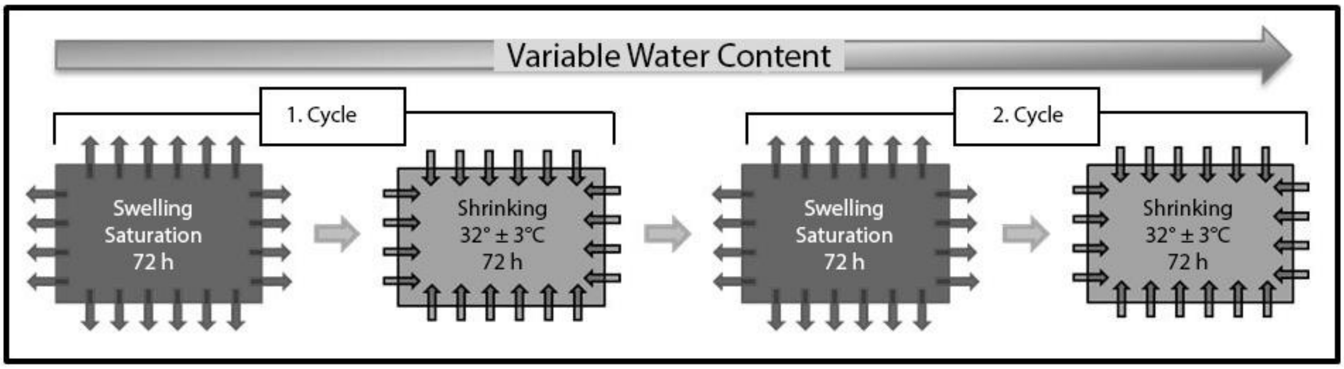

Figure 2. Experimental procedure of two swell-shrink cycles at varying water content

Vegetation experiment

The influence of intact vegetation and its root system on the dredged material was simulated by sowing a mixture of grasses. An experimental field (1 m x 1 m x 0.2 m) was prepared where the dredged material was installed in three layers with a defined bulk density (0.96 g/cm^3) and a grass mixture was sown. The site was irrigated in dry periods and directly after seeding to ensure optimum plant growth. The area was fertilized after four weeks to ensure a good supply of nutrients. The grass was cut back weekly with a hand mower. After completion of the experiment (12 weeks), 24 undisturbed soil cores were taken at a depth of 2-7 cm (6 to determine the water retention parameters and 18 for measuring the saturated hydraulic conductivity).

Measuring the physical parameters

The determination of the water contents at pF 1.8 (field capacity) was carried out in vacuum box and at pF 4.2 with a pressure plate apparatus (DIN 11274, 2011). The pore volume was calculated from air content (air pycnometer) and water content. The saturated hydraulic conductivity was determined with an Eijkelkamp permeameter in accordance with DIN ISO / TS 17892-11 (2005).

Results and Discussion

Table 1 shows an overview of the hydraulic parameters of the dredged material after freeze-thaw cycles, swelling and shrinkage and in the vegetation experiment.

Table 1. Changes of the physical parameters due to freeze-thaw (FT), swelling and shrinkage (SS) and in the vegetation experiment (different letters denominate statistically significant differences; significance level 5%)

Freeze-thaw cycles						
Parameter	Initial values		After 7 FT cycles		After 14 FT cycles	
FC [%v/v]	52.9	(a)	47.1	(b)	45.3	(b)
AWC [%v/v]	18.2	(a)	11.7	(b)	10.5	(b)
Layer width for 140 mm AWC [dm]	7.7		12.0		13.3	
Layer width for 220 mm AWC [dm]	12.1		18.8		21.0	
AC [%v/v]	10.5	(a)	13.7	(a)	20.1	(b)
PV [%v/v]	63.4	(a)	60.8	(a)	65.4	(a)
PWP [%v/v]	34.7	(a)	35.4	(a)	34.8	(a)
Ks [m/s]	$5.35 \cdot 10^{-7}$	(a)	$8.68 \cdot 10^{-6}$	(b)	$3.72 \cdot 10^{-5}$	(c)
Swell-shrink						
Parameter	Initial values		After 7 SS cycles		After 14 SS cycles	
FC [%v/v]	52.9	(a)	50.4	(a)	42.2	(b)
AWC [%v/v]	18.2	(a)	15.9	(a)	6.9	(b)
Layer width for 140 mm AWC [dm]	7.7		8.8		20.3	
Layer width for 220 mm AWC [dm]	12.1		13.8		31.9	
AC [%v/v]	10.5	(a)	12.6	(a)	20.1	(b)
PV [%v/v]	63.4	(a)	63.0	(a)	62.3	(a)
PWP [%v/v]	34.7	(a)	34.5	(a)	35.3	(a)
Ks [m/s]	$5.35 \cdot 10^{-7}$	(a)	$3.30 \cdot 10^{-6}$	(b)	$5.22 \cdot 10^{-6}$	(c)
Vegetation experiment						
Parameter	Initial values				After 12 weeks	
FC [%v/v]	52.9	(a)			45.3	(b)
AWC [%v/v]	18.2	(a)			12.1	(b)
Layer width for 140 mm AWC [dm]	7.7				11.6	
Layer width for 220 mm AWC [dm]	12.1				18.2	
AC [%v/v]	10.5	(a)			21.4	(b)
PV [%v/v]	63.4	(a)			66.7	(a)
PWP [%v/v]	34.7	(a)			33.2	(a)
Ks [m/s]	$5.35 \cdot 10^{-7}$	(a)			$2.05 \cdot 10^{-4}$	(b)

The field capacity (FC) was significantly reduced due to freeze-thaw cycles (FT) and swell-shrink cycles (SS) from 52.9 %v/v (initial value) to 45.3 %v/v (after 14 FT cycles) and to 42.2 %v/v (after 14 SS cycles). Similar changes were observed in the vegetation experiment (reduction to 45.3 %v/v after 12 weeks). The differences between initial values and final values are statistically significant. All FC values are classified as "very high" according to the German standard (Boden, 2005).

The available water capacity (AWC) was also significantly reduced in the course of the experiment from 18.2 %v/v (initial value) to 10.5 %v/v after 14 FT cycles to 6.9 %v/v after 14 SS cycles and to 12.1 %v/v in the vegetation test after 12 weeks. The differences between initial values and final values are statistically significant. The initial field capacity is classified as "medium" and at the end of the experiments in each case as "low" according to the German standard [10]. The required layer thickness for cover layers of landfills to achieve 140 mm AWC (7.7 dm) or ET layers to achieve 220 mm AWC (12.1 dm) increased significantly to 13.3 and 21.0 dm (FT cycles), to 20.3 or 31.9 dm (SS cycles), and to 11.6 and 18.2 dm (vegetation experiment), respectively. These figures hold under the assumption that the entire cover layer or water retaining layer has aged accordingly.

The air capacity (AC) increased continuously in the course of the experiment from initially 10.5 %v/v to 20.1 %v/v after 14 FT cycles and to the same value after 14 SS cycles and to 21.4 %v/v in the vegetation test after 12 weeks. The differences between initial values and final values are statistically significant. The initial AC is classified as "medium" and at the end of the experiments as "high" according to the German standard (Boden, 2005).

Changes in the pore volume (PV) and the water content at the permanent wilting point (PWP) are very small and not statistically significant. The PV and the PWP for all measurements are classified as "very high" according to the German standard (Boden, 2005).

The saturated hydraulic conductivity (Ks) increased statistically significant with the number of FT cycles in all studies. The initial Ks value is classified as "low" and after 7 and 14 FT cycles "high" and "extremely high" (Boden, 2005). After 7 and 14 SS cycles the Ks values are classified as "medium". Even larger differences exist in the vegetation experiment. Here, the Ks value after 12 weeks is "extremely high" (Boden, 2005).

In summary it can be stated that 14 freeze-thaw cycles, 14 swell-shrink cycles and 12 weeks vegetation experiment have a very similar and significant impact on the parameters FC, AWC, AC and Ks in the investigated dredged material while the impact on the PV and PWP were negligible. Major results are that PV and water content at PWP have remained the same, AC and Ks increased while FC and AWC decreased.

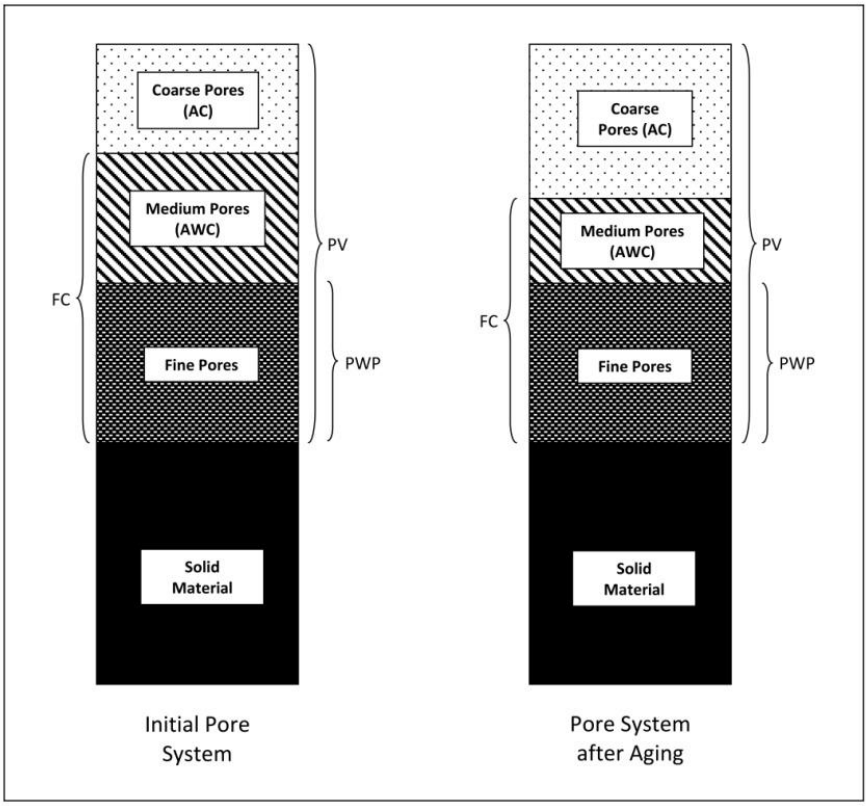

Figure 3. Changes in the pore system due to aging

Figure 3 shows this result in schematic form: The proportion of solid soil material must remain constant over long time periods, as long as minerals are not dissolved and relocated. Since the PV and the PWP (fine pores) also remained practically constant in the course of the experiment, an increase in the coarse pore fraction (AC) must result in a reduction in the medium pores (AWC) in the same magnitude. Table 2 shows a summary of the effect of artificial aging on the dredged material as differences to the initial values.

Table 2. Changes of the physical parameters as differences to the initial values (significance level 5%)

	FC [%v/v]	AWC [%v/v]	AC [%v/v]	PV [%v/v]	PWP [%v/v]	Ks [m/s]
Freeze-thaw cycles						
7 cycles	-5,73	-6,49	+3,04 (n.s.)	-2,65 (n.s.)	+0,77 (n.s.)	$+0{,}81\cdot10^{-5}$
14 cycles	-7,61	-7,69	+8,29	+2,0 (n.s.)	-0,10 (n.s.)	$+3{,}67\cdot10^{-5}$
Swell-shrink cycles						
7 cycles	-2,43 (n.s.)	-4,55 (n.s.)	+4,01 (n.s.)	-0,4 (n.s.)	-0,12 (n.s.)	$+0{,}28\cdot10^{-5}$
14 cycles	-10,72	-11,32	+8,25	-1,15 (n.s.)	+0,61 (n.s.)	$+0{,}47\cdot10^{-5}$
Vegetation experiment						
15 Weeks	-7,57	-6,08	+9,55	+3,3 (n.s.)	-1,48 (n.s.)	$+20{,}45\cdot10^{-5}$

Abbreviations: (FC): field capacity; (AWC): available water capacity; (AC): air capacity; (PV): Pore volume; (PWP): permanent wilting point; (n.s.): non-significant

The decrease in field capacity can be explained with a reorganization of the pore system as a result of freezing and thawing. Due to volume expansion of the pore water during freezing new coarse pores are formed. This results in a decrease of the FC and AWC at constant total pore volume. According to Tresselt (2000), a decrease in FC of 3.7 %v/v has been observed after only two years under the influence of pedogenic and biogenic processes in a field experiment. Bronick and Lal (2004) also indicate a short-term effect of freeze-thaw cycles on pore formation and soil aggregation. The change of the pore system as a result of swelling and shrinking processes is caused by similar processes as freeze-thaw cycles. Due to the mechanical action of swelling and shrinkage and the associated shift, aggregation and rounding of aggregates, the proportion of coarse pores increases (Blume et al., 2010). Volume expansion (swelling) and subsequent volume reduction (shrinkage) of the swellable clay fraction result in a modification of shape and layout of the aggregates. The dredged material has a clay content of 27%w/w, which generally allows swelling and shrinkage processes.

During the experiment, shrinkage cracks of more than 1 cm in width were observed up to 3 cm deep. It could also be observed during sampling that under the influence of swelling and shrinkage the coherent structure changed to an aggregate structure.

The influence of plants on the soil structure and its intensity is mainly due to the different nature of root formation and vegetation density. It is effective primarily in the topsoil, because here the rooting is most intense. Thus a stable crumb structure with a high porosity is established under pasture by the root system without anthropogenic influence (Blume et al., 2010).

At the start of the experiments of artificial aging the dredged material had a coherent structure. Under the influence of freeze-thaw and swell-shrink dynamics an aggregate structure was formed. Under the influence of the roots a crumb structure was formed in the field. In the upper 10 cm high rooting intensity was observed. Consequently, the intensive structure formation was restricted to this depth. The effect of the root formation on soil structure is mostly controlled by the vegetation density and the resulting rooting intensity. Thus, a stable crumb structure is developed under extensively managed grassland (Blume et al., 2010). Secondary coarse pores have been formed under the influence of plant roots. As with other processes, there is a redistribution of the pore volume increasing the amount of coarse pores and decreasing that of the medium pores.

The decrease of the FC (at simultaneously constant PWP) explains the decrease in the AWC to a similar extent, e.g. after 14 the freeze-thaw cycles a reduction of the FC of 7.61 %v/v and of the available water capacity of 7.69 %v/v. This is true for all other variants to a similar extent. Due to the formation of large pores, the air capacity (AC) of the aged dredged material increased. A significant increase of 8.3 %v/v was found at the expense of the FC and the AWC. Similar increases in AC are reported by Tresselt (2000) in a topsoil field trial (7.1 %v/v). Similar values were also reported on another site with dumped harbor sediment (Schneider, 2005). Here, too, new coarse pores were formed as inter-aggregate voids under the influence of natural aging.

With respect to the permanent wilting point (PWP), no significant differences were found, because the PWP is only determined by the fine pores which are material dependent and not affected by the influence of freeze-thaw or swell-shrink cycles (Blume et al., 2010). For an increase in the proportion of fine pores new formation of finely dispersed substance (new formations after weathering, such as clays, or organic degradation products and oxides), which is incorporated in situ or by relocation from adjacent horizons would have to occur (Blume et al., 2010). For an effect of these slowly progressing pedogenic processes the experiment duration was too short.

The saturated hydraulic conductivity (Ks) significantly increased by artificial aging to high and very high values. Key factor for Ks is the number, size and shape of the pores. Soils with a high proportion of coarse pores generally show high Ks values. The increase of coarse pores is accordingly reflected in the increase of the measured Ks values. However, the most important modification with respect to hydraulic conductivity is the described structure formation in the material, where a loose aggregate structure was formed from the dense coherent structure by the aging processes.

The effect of artificial aging in longer time periods is difficult to assess. An agriculturally used soil made of similar dredged material shows after 25 years a coarse pore volume in the topsoil comparable with the results of artificial aging in this paper (Blume et al., 2011).

It can be assumed that the coarse pore volume resulting as an effect of artificial aging is already in the climax stage of development.

In Central Europe 2-3 freeze-thaw cycles per year can be expected at a depth of 50 cm (Blume et al., 2011). Thus, 14 freeze-thaw cycles correspond to approximately 5 to 7 years under natural climate impact, implying that the climax of the structural development is achieved soon. With less pronounced freeze-thaw cycles (e.g. close to the coast or due to expected climate change) the consequent changes in structure would penetrate less deeply and the duration for the natural structure change would be extended. With respect to the decrease of the medium pore volume due to the artificial aging, similar values are reported from other sites made of dredged material. From studies of artificial soils at other places it is also apparent that structural modifications due to aging of the substrate strongly decreases or ceases at soil depths below 50 cm (Blume et al., 2011).

Conclusion

The comparison of the physical properties of the investigated dredged material with the requirements for cover layers or ET layers according to the German regulatory requirements showed that directly after installation of the material the air capacity (11 %v/v) was only slightly above the minimum value of 8 %v/v. After artificial aging the material has an AC of about 20 %v/v which can expect a good plant development.

Directly after installation (or determined at artificially compacted samples in the laboratory) the AWC is sufficient for a cover layer (or ET layer) if the layer thickness is larger than 8 (or 12) dm, respectively. This will be the case for all practical applications of landfill covers. However, the artificially aged dredged material shows a significant reduction of the AWC. The required layer thickness in the extreme case after 14 swell-shrink cycles is 20 dm (cover layer) or 32 dm (ET layer). This needs to be considered when planning a landfill cover.

However, the described modifications of the pore system will not reach several meters deep down into the ground in the field. Freeze-thaw and swell-shrink processes will penetrate the top layer to a maximum depth of 50 to 100 cm; below this depth rather the initial values must be considered. This relativizes (and decreases) the necessary layer thicknesses described above for cover or ET layers of landfills and should possibly be considered in the legal regulations.

The development of the process of aging under natural conditions is difficult to assess. Freeze-thaw cycles can, for instance, be quantified according to locally measured freeze-thaw cycles numbers. The assessment of swelling and shrinkage phases, however, is significantly more complicated to estimate [14]. An effect of intact grassland vegetation in the first 10 cm of topsoil can be detected already after 15 weeks based on the vegetation experiment, but only in the investigated depth of 5-10 cm. An interdependency of the processes described could not be clarified in this investigation.

With respect to the suitability of the investigated dredged material as material for landfill cover layers, the results indicate that the specified minimum values for AWC capacity must be rather increased due to a possible decrease over time. The measured average decline of 6 %v/v AWC and assumed penetration depths of the aging processes in the upper third of the cover layer would result in a rather small increase in the necessary layer thickness of a few decimeters only to meet the legal requirements.

Much more important for practical considerations is the increase of the air capacity due to aging processes, which is of considerable importance especially in the upper part of the landfill cover for the growth of plants. Thus, the often described risk of a too low air capacity for optimum plant growth due to strong compaction by machines is slightly less important because of increasing air capacity with aging. The results are surely not universally transferable to other soil materials. Materials rich in sand will very likely show much less pronounced changes due to less swelling and shrinkage. Such materials, however, are not much used as landfill top layers because of the low AWC. The key difference of the investigated dredged material in comparison with loamy natural soil material typically used for landfill cover layers is the lower bulk density. Future investigations will show to what extent this has an influence on the soil structural development.

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