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MATURED DREDGED MATERIAL AS RESTORATION SUBSTRATE IN LANDFILL SURFACE SEALING SYSTEMS

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Abstract. The German Landfill Ordinance requires proof of a sufficiently large field capacity for recultivation layers. In Mecklenburg-Vorpommern humus-rich and fine-grained substrate is prepared from the dredging of shipping lanes and has been used for about 15 years as landfill recultivation substrate. On four landfill sites the production and effectiveness of recultivation layers made out of matured dredged material (DM) were examined. For this purpose the used dredged material was analysed. The current functionality of the recultivation layers was examined by soil chemical and soil mechanical investigations.

Keywords: dredged material, recultivation, restoration, landfill, sealing system, field capacity, HELP

1. Introduction

Landfills must be secured after operation. This closure, "encapsulation" from the environment, is performed using a surface sealing system. The upper layer of this system is composed of a recultivation substrate.

The Landfill Ordinance (Ordinance on Landfill Sites and Long-Term Storage Facilities - Landfill Ordinance) (DepV 2012) sets out requirements for the recultivation layer (function and substrate).
Additional requirements on the recultivation layer are described in the recommendations of the German Geotechnical Society (DGGT - Deutsche Gesellschaft für Geotechnik e.V.; recommendations E 2-31 and E 2-32) (GDA 2006; GDA 2010) and Nationwide Quality Standards (BQS 7-1 2011; BQS 7-2 2011).

Currently, the feasibility of soil physical demands arising from the Landfill Ordinance is discussed extensively.
It is checked what challenges arise for the life praxis of landfill construction thereof.

In Mecklenburg-Vorpommern more than ten landfills have already been restored with matured dredged material from coastal waters since the late 90s.

Due to the new requirements for substrates for recultivation layers by the current landfill regulations, already sealed landfills with matured dredged material were examined. It was examined, whether the already existing recultivation layers meet these requirements. Can matured dredged material be installed in recultivation layers in the future?

2. Origin and Quality of the dredged material

The dredged material comes from waterways and harbours. Only the dumping of sand and marl in the Baltic Sea is allowed. Dredged Material with rich content of humus, silt and clay must be disposed of on land in mono disposal sites (including dewatering/flushing fields).

In Rostock this dredged material is classified, dewatered and processed in specially-developed inland disposal sites. The conditioned dredged material can be used for different purposes. The material is similar to an organic-rich, clayey-silty soil or loam.

Since the late 70s of last century, research is being conducted in Rostock for an environmentally responsible use of dredged material. The inland disposal sites of the Hanseatic City of Rostock were converted mid-90's to an industrialised dewatering and treatment system.

Thus, environmentally sound and efficient management of dredged material is possible. Law requirements are met. Since 2000 Rostock utilized his dredged material (rich in organic matter and silt/clay) to 100% onshore. The recovery takes place mainly in landscaping and landfill restoration (Fig. 1).

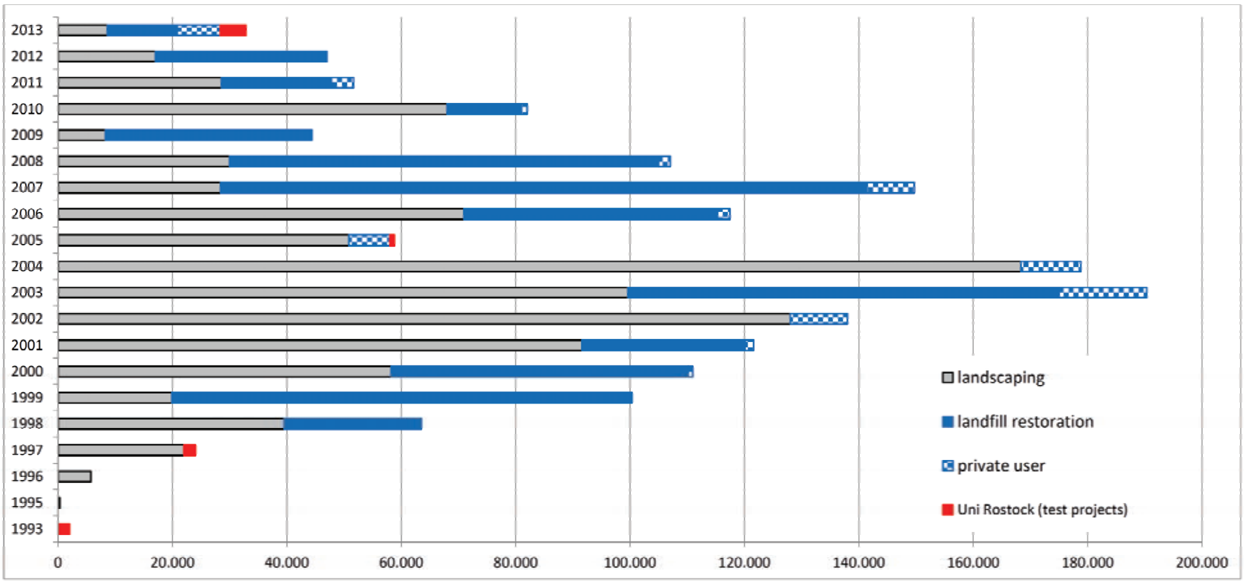

Fig 1. Development of the utilisation of the Rostock dredged material (tons per year)

Table 1: Particle size distribution (%) of the matured dredged material (DIN ISO 11777) (arithmetic mean value = average)

	Coarse sand	Medium sand	Fine sand	Coarse silt	Medium silt	Fine silt	Clay
average silt	1,1	8,7	29,9	10,8	15,5	11,5	23,6
average mixed soil	1,4	16,3	56,4	8,5	57,0	3,0	8,3
maximum silt	3,0	22,0	49,0	18,0	27,0	19,0	46,0
maximum mixed soil	3,6	28,9	70,9	14,2	103,0	4,6	15,1
minimum silt	0,0	1,0	7,0	7,0	8,0	6,0	13,0
minimum mixed soil	0,4	7,7	45,7	3,5	26,0	1,5	3,0

Table 2: Nutrient and salt content of silt and mixed soil

	DM	pH	SK	Cl^-	Na^+	SO_4	OM	$CaCO_3$	anorg. N	P	K	Mg	total N	exchange capacity
	%		%	mg/100 g soil				%		mg/100 g			%	mval/ 100g soil
			DM	DM	DM	DM	DM	DM	DM	DM	DM	DM	DM	
average silt	58,2	7,3	1,9	429	346,1	514,8	11,1	8	2,5	2	31,4	127,8	0,5	26,1
average mixed soil	71,3	7,4	1,2	140,9	114,5	264,2	5,3	5,6	0,9	1,8	12,8	67,7	0,2	9,2
maximum silt	71	8	4	1340	905	1428	18	16	9	5	56	226	1	36
maximum mixed soil	87,5	7,9	2,5	678,8	422	541,9	11	9,8	2	4,4	19,5	125	0,5	14,6
minimum silt	47	7	1	69	104	163	4	2	1	0,4	9	72	0	16
minimum mixed soil	60,1	7,0	0,4	11,5	28,0	82,0	0,9	2,5	0,5	0,4	7	14,8	0,1	4,4

OM – organic matter; DM – dry matter; SK – salt

2.1 Particle size distribution (Soil Texture)

The dredged sediments are flushed into confined disposal facilities (CDF) via pipeline. The dredged material has a water content of approximately 95%. A confined disposal facilities is a diked area on land, used to contain dredged material. The CDF are used interchangeably. The particles classify in the CDF along the water stream. Stones, gravel and sand are not carried away by the water very far, at the end of the flowing water the finer and lighter components are deposited (silt, clay and organic matter) (Table 1).

The sands and gravels can be used in the construction industry. Far along in the water stream a mix of different particle sizes will settled down (mixed soils = sand-silt mixtures) and farthest from the inlet the fines particles settle down (clay-silt mixtures with organic matter). The classification along the current leads to two suitable fractions for landfill restoration (*mixed soils* and clay-silt mixtures with organic matter, called *silt*).

2.2 Chemical characterization of wet dredged material

The origin of the dredged material from the coastal area leads to naturally elevated salinities (SK) (Table 2). The dredged material in Rostock is mainly influenced by the river Warnow. The Warnow flows into the Baltic Sea near Rostock. The river Warnow has a rural drainage area.

The waste water of the entire drainage area is cleaned in sewage treatment plants. Therefore, the pollutant content in the dredged material is relatively low. After classification of the dredged material in the upland CDF the silt is more polluted than the mixed soil (Table 3; Table 4). Compliance with the specific utilization limit and guideline values allows a wide range of applications such as the use in landfill restoration.

3. Use of matured dredged material in landfill restoration

Since the late 90's treated dredged material (mixed soil and silt) is used in landfill restoration. Dredged material (mainly silt) is even used in gardening, landscaping and agriculture. Especially silt has very good characteristics (nutrient holding capacity, erosion stability).

The use of the dredged material in landfill cover systems was approved individually by the authorities. Exceptions are necessary since the dredged material contains great amounts of salt and organic matter. The recommended values of the Landfill Ordinance are significantly exceeded.

The dredged material is suitable for both, forming the landfill, as well as, for building a restoration and water management layer. In Mecklenburg-Vorpommern soil material is needed for the closure of landfills and as cover of contaminated sites.

The Landfill Ordinance defines properties, which the recultivation layer has to fulfil. The recultivation

Table 3: Pollutant content of silts and mixed soils; and limit values

	Pb	Cd	Cr	Cu	Ni	Hg	Zn	As	EOX	IR-hydrocarbons	PAH	PCB
	mg/kg DM											
average silt	21,2	0,4	35,2	22,4	14,5	0,3	100,5	9,6	0,7	225,3	0,9	0,033
average mixed soil	9,5	0,2	15,8	12,0	6,7	0,2	44,2	5,8	0,7	108,7	0,6	0,028
maximum silt	35,0	0,8	63,5	37,0	18,0	0,9	177,0	25,0	1,0	715,0	2,18	0,074
maximum mixed soil	23,8	0,3	32,8	28,5	10,0	0,4	94,0	12,5	1,3	281,0	3,3	0,066
minimum silt	10,0	0,0	12,0	14,0	11,0	0,0	36,0	5,0	0,0	28,0	0,0	0,009
minimum mixed soil	4,0	0,1	44,0	4,6	3,0	0,0	16,0	3,6	0,4	19,4	0,0	0,009
BBodSchV VSW sand	40,0	0,4	30,0	20,0	15,0	0,1	60,0				3,0	0,050
70%	28,0	0,3	21,0	14,0	10,5	0,07	42,0				2,1	0,035
BBodSchV VSW loam/silt	70,0	1,0	60,0	40,0	50,0	0,5	150,0				3,0	0,050
70%	49,0	0,7	42,0	28,0	35,0	0,35	105,0				2,1	0,035
DepV (recultivation layer)	140	1	120	80	100	1	300				5	0,1

DM – Dry Matter; BBodSchV - Federal Soil Protection and Contaminated Sites Ordinance; DepV – Landfill Ordinance; VSW - precautionary value

Table 4: Pollutant content (eluate) of the silts and mixed soils and limit values according landfill ordinance

	pH	Lf	Chloride	Sulphate	Pb	Cd	Cr	Cu	Ni	Hg	Zn	As
		µS/cm	mg/l		µg/l							
average silt	7	4044	542	2022	9,1	0,6	2,3	28,8	10,6	n.n.	75,8	3,4
average mixed soil	7,1	2975	259	1596	4,6	0,2		11,3	6	n.n.	21,7	2,2
DepV (recultivation layer)	6,5 - 9	500	10	50	40	2	30	50	50	0,2	100	10

Lf – conductivity; DepV – Landfill Ordinance; VSW - precautionary value; n.n. - undetectable layer should offer a high water storage and good plant available water capacity, helping so to reduce leachate formation. Even a temporary cover has to minimize leachate formation. The recultivation substrate also needs to ensure an adequate plant growth, a field capacity of at least 140 mm, based on the total thickness of the recultivation layer, is required (Landfill Ordinance, Appendix 1, section 2.3.1).

When establishing a water regime layer, the Landfill Ordinance calls for a field capacity of at least 220 mm, based on the total thickness of the water regime layer. In addition, the seepage may not exceed 10 percent of the long-term average of precipitation (usually 30 years), not more than 60 mm per year (Landfill Ordinance, Appendix 1, section 2.3.1.1). Matured dredged material also has to fulfil the requirements for landfill replacement construction materials (DepV, Annex 3, Table 2, item 9 of Table 1).

To continue the use of mature dredged material in the landfill restoration, it has to be tested on already reclaimed landfills if the new requirements of the Landfill Ordinance (for example available water content) are complied. Observations on reclaimed landfills and experience in other fields of application of dredged material give reason to believe that the material is able to comply with the new Landfill Ordinance.

In a lysimeter test the leachate quantity was reduced up to 25% compared to loamy sand by using dredged material (silt) incorporated in the soil.

4 Results – Test of restoration layers

For the investigations four disposal sites covered with dredged material were selected.
Following parameters at the four sites were tested:

- Current situation (leachate quantity, special problems)
- Visual assessment of the cover layer (plant growth, erosion, settlement, landslide ...)
- soil sampling (disturbed and undisturbed samples) to evaluate the residual shrinkage of the dredged material and to determine the root depth and intensity
- Geotechnical investigations under Landfill Ordinance or German Geotechnical Society recommendation (water contents, densities, shear strength on site, current field capacity (field capacity and available water content), coefficient of permeability (in-situ and laboratory), pH, organic matter, lime content
- Assessment of pollutants in the dredged material
- Investigation of the material displacement, especially salts transfer in the profile
- Examination of humus forms in the dredged material and its stability (AT_4 respirometric activity)
- Modelling the water balance with the Hydrologic Evaluation of Landfill Performance Model (HELP version 3.90D)

The age of the recultivation layers was different. The landfills have been covered two to 16 years ago. The matured dredged material used for the restorations varies in its chemical and physical properties, because it comes from different dredging. None of the test fields had the same dredged material; all studies were carried out on already secured landfills.

4.1 Current Situation

During and after the restoration the landfills were visited often. Among others the maintenance state after restoration was recorded. If the landfills were mowed annually, grasses form the dominant plant species. If there is no maintenance (no mowing) for years, herbs and brushes grow, and first trees grow. At all landfills dense vegetation exists (high soil fertility of the substrate dredged material despite the increased salinity).

None of the landfills showed mechanical changes on the surface (erosion, slides or subsidence). The very intense rainfall of 2011 could not harm the recultivation layers. Leachate in the drainage layer of the sealing system could be observed only in one landfill. In excavation tests, cracks in the restoration layer could be observed. This was especially the case when the water content was too high during installation of the dredged material. The cracks reach several decimetres in the restoration layer. However, the shrinkage cracks are filled with soil particles. The recultivation layers are very well rooted and are tapped for water supply of the plants and evaporation loss.

4.2 Evaluation of chemical and biological characteristics of the recultivation layers

Each of the four investigated landfills was sampled at two points in the entire restoration layer (about one meter deep). The measurements and the sampling were performed in three depths.

The water movements in the restoration layer led to material relocation. Especially salt and magnesium ions usually show an increase in their content with the depth. The contents of total organic carbon and lime show similar high levels as during the installation of the dredged material. The high lime content receives long-term neutral pH values (high buffering capacity). The high level of total organic substance shows the very good stability of the organic matter. The respirometric activity (AT_4) is well below the specification of the landfill ordinance (5 mg O_2/g dry matter). The relevance of origin-related high salt content in the dredged material has already been highlighted.

But individual decisions enable the reasonable use of the dredged material. The relatively low levels of available nitrogen (compared to the large supply of nitrogen in the soil) in the upper mineral recultivation layer are sufficient to enable a strong plant growth. The dredged material is low in available mineral nitrogen (0.5 to 2 mg N_{min}/100 g of soil; about 20 - 80 kg N/ha in the upper restoration layer of 0 - 30 cm).

The levels of plant-available phosphorus are low, as known from the fresh dredged material. To satisfy

Table 5: Chemical ccharacteristics of recultivation layers

landfill	depth	dry matter	pH	salt	Cl^-	Na^+	SO_4^{2-}	organic matter	AT_4	$CaCO_3$	N_{an}	P	K	Mg
				grav.		dry matter							dry matter	
	mm	%		%		mg/100 g soil		%	mg O_2/kg DM	%			mg/100 g dry matter	
M 1	100	78,7	7,2	0,19	1,9	1,2	138,2	4,8	1,0	3,6	1,3	4,5	17	37
	350	78,3	7,4	1,03	2,0	1,3	174,3	4,8	0,7	3,2	0,8	1,7	10	34
	700	75,2	7,5	1,13	0,7	3,8	187,1	6,9	1,0	3,8	0,9	1,9	9	74
M 2	150	71,1	7,3	0,8	0,5	1,1	66,8	7,6	1,0	3,1	0,7	5,1	16	44
	400	73,2	7,4	1,05	2,0	2,0	179,4	5,6	0,9	3,3	0,3	2,2	10	37
	750	67,8	7,5	1,13	1,4	3,9	207,5	7,8	1,1	4,7	0,4	1,5	9	72
N 1	150	61,8	7,5	1,1	4,4	7,4	284,8	8,2	1,5	3,4	0,8	1,2	17	37
	450	66,8	7,7	1,4	59,4	90,0	271,7	7,4	0,6	3,4	1,6	0,8	13	79
	850	62,9	7,6	1,6	152,5	149,0	307,8	7,0	1,1	2,4	2,2	0,7	14	76
N 2	150	76,9	7,6	1,1	11,5	11,0	205,5	7,4	0,8	3,8	1,2	1,0	22	40
	400	72,1	7,6	1,6	103,1	128,0	274,9	8,7	1,3	2,9	1,8	0,7	12	92
	850	69,9	7,6	2,0	329,1	218,8	286,1	9,8	0,8	2,7	1,7	1,3	17	102
	1200	66,5	7,7	1,7	210,3	159,1	283,3	8,3		3,0	1,5	0,5	20	95
T 1	400 - 500	75,5	7,6	1,1	8,2	13,7	227,5	5,3	0,4	5,1	0,9	0,7	9	54
	800 - 850	70,2	7,6	1,3	35,1	55,1	262,4	6,5	0,6	4,2	1,1	0,6	13	77
T 2	350 - 450	63,1	7,6	1,19	11,7	27,3	287,5	9	0,8	4,8	1,3	0,7	11	82
	800 - 850	72,2	7,6	1,21	17,4	34,3	249,9	6,1	0,6	4,6	1,0	0,6	11	71
G 1	100 - 200	74,4	7,6	1,12	5,0	8,8	219,4	9,7	1,8	2,7	0,9	0,9	16	58
	400 - 500	66,5	7,6	1,26	14,2	29,5	244,8	8,9	0,9	2,0	0,9	0,6	13	95
	800	62,2	7,6	1,54	102,8	110,3	298,4	9,8	2,6	2,4	1,0	0,4	20	100
	950	64,2	7,6	1,51	95,0	103,9	307,5	8,6		1,8	0,9	0,4	20	97
G 2	200 - 250	74,4	7,6	1,11	7,3	9,4	232,3	11,3	1,9	2,6	1,3	0,6	14	48
	550	58,7	7,6	1,53	79,4	116,2	331,5	12,8	2,0	4,8	1,5	0,3	23	110
	800	57,1	7,6	1,62	130,1	148,1	349,2	11,8	1,9	4,3	1,4	0,3	25	105

the plant's needs, the content is sufficient. The levels of plant-available potassium are adequate. There is no additional fertilization required. The levels of plant-available magnesium are high to very high (35-100 mg/100 g soil). Freshly processed dredged material contains even more than 150 mg /100 g soil) (Table 5).

The investigation of soil chemical parameters shows that the dredged material has a very good soil fertility determining properties for plant growth. (Table 5). Due to the good binding capacity (high contents of total organic content and clay) as well as the excellent water holding capacity no increased discharge of salt ions and nutrients is expected.

4.3 Evaluation of physical properties in the recultivation layers

The Landfill Ordinance and the Nationwide Quality Standards BQS 7-1 "recultivation layers" and BQS 7-2 "water regime layers" (BQS 7-1 2011; BQS 7-2 2011) require compliance with soil physical parameters (see Chap. 3). These parameters were tested in order to prove whether the further use of the treated and matured dredged material (mixed soil and silt) for landfill closure can be allowed.

4.3.1 Shear Strength

The in-situ shear strengths (investigated with Field Vane Shear Apparatus) vary considerably depending on the installation of the dredged material in the restoration layer. On landfills where the dredged material was slightly compacted during installation or where marl was installed as the top layer of restoration layer, high shear strengths of 70 to 80 kPa and even 100 to 120 kPa were measured, also in the top layer.

The measurements on other landfill recultivation layers have a clear depth-related graduation. In the upper, loosely built layer, the determined shear strengths were only about 20 to 33 kPa. This looseness is particularly due to the high content of organic matter and the intensive rooting. In the underlying layers shear strengths were measured by more than 100 kPa (Table 6).

Table 6: In-situ shear strength of the restoration layers (field vane test)

landfill	depth	dry matter	In-situ shear strength	bulk density
	mm	%	kPa	g/cm³
M 1	150	78,7	26,5	1,11
	700	75,2	156,8	1,14
M 2	100	71,1	18,4	1
	350	73,2	21,3	0,98
	650	67,8	116,6	1,05
N 1	450	66,8	30,3	0,9
	1000	62,9	35,0	0,9
N 2	150	76,9	32,7	0,9
	400	72,1	116,7	0,9
	850	69,9	109,1	0,9
T 1	400 - 500	75,5	116,7	1,1
	800 - 850	70,2	109,1	1,0
G 1	100 - 200	74,4	122,0	0,9
	400 - 500	66,5	136,0	0,9
	800	62,2	124,0	0,9
G 2	200 - 250	74,4	103,5	0,82
	550	58,7	92,8	0,77
	800	57,1	97,1	0,83

4.3.2 Hydraulic conductivity

The determination was carried out in the field with a Double ring infiltrometer (unsaturated conductivity) and in the laboratory (saturated conductivity) with sampling rings (500 cm³ or 250 cm³).

The hydraulic conductivity of the recultivation layers is very low. There was no targeted consolidation of the built-in layers. The installation was done with bulldozer or excavator. The hydraulic conductivity varies as a function of the analytical method between 8.1 x 10-6 and 1.2 x 10-7 m/s (laboratory method) or 2.18 x 10^{-6} and 1.98 x 10^{-8} m/s (field method) and decreases from top to bottom.

4.3.3 Pore volume and soil bulk density

The total pore volume (total porosity) of the restoration layers (matured dredged material) is even after several years (including losses due to possible minor settling after installation) usually about 50%, often over 60%. This large pore volume is also shown in the very low bulk densities of mostly 0.8 to 1.1 g/cm³ (Table 7). Both are independent of the depth.

After installation no significant settlements of the recultivation layers have occurred.

4.3.4 Field capacity, available water capacity and air capacity

The high total pore volume also enables high field capacity and available water capacity. Because of the high quantity of medium and fine pores (silty-clayey dredged material; silt), the majority of the total pore volume can hold water against gravity (very high field capacity, often more than 50%).

Often, more than half, but at least more than 35% of the pore volume is available for plants. The available field capacity is almost always more than 20% by volume, in some cases even more than 30% by volume.
The requirements of the Landfill Ordinance by 140 mm (recultivation layer) or 220 mm (water regime layer) field capacity are always satisfactory, even years after the installation of the recultivation layer.

Water regime layers can also be produced from dredged material (Table 7).

The low bulk density also results from the large air pore volume. In the top soil layer (0-30 cm) the air pore volume (air capacity) is partly greater than 10%. In combination with the very good water supply (very high available field capacity) and adequate available nutrients excellent conditions for rapid plant growth are given.

Table 7: Soil physical properties of the restoration layers

landfill	depth	dry matter	organic matter	$CaCO_3$	bulk density	density	PV	WV	AV	FC	aFC	aFC/FC
	mm	%	%	%	g/cm3	g/cm3			Vol %			%
M 1	100	78,7	4,8	3,6	1,11	2,52	56,1	37,9	6,1	50,0	33,7	67,4
	350	78,3	4,8	3,2	1,10	2,52	56,2	43,6	8,8	47,4	29,5	62,3
	700	75,2	6,9	3,8	1,14	2,47	53,8	49,1	0,8	53,0	23,4	44,1
M 2	150	71,1	7,6	3,1	1,00	2,49	59,7	37,4	4,8	54,9	37,2	67,9
	400	73,2	5,6	3,3	0,98	2,51	61,2	41,0	11,8	49,4	29,1	59,0
	750	67,8	7,8	4,7	1,05	2,47	57,3	45,4	4,2	53,2	20,5	38,6
N 1	150	61,8	8,2	3,4	0,88	2,42	63,8	49,3	12,5	51,3	25,9	50,5
	450	66,8	7,4	3,4	1,03	2,45	58,1	46,7	5,6	52,4	24,1	45,9
	850	62,9	7,0	2,4	0,89	2,45	63,8	55,8	7,9	55,9	35,1	62,8
N 2	150	76,9	7,4	3,8	0,87	2,48	64,7	32,0	25,6	39,1	21,1	54,1
	400	72,1	8,7	2,9	0,90	2,43	62,8	43,3	9,7	53,1	30,2	56,8
	850	69,9	9,8	2,7	0,88	2,42	63,6	42,3	8,9	54,7	28,7	52,5
T 1	400 - 500	75,5	5,3	5,1	1,12	2,54	51,4	49,7	6,1	45,3	20,2	44,5
	800 - 850	70,2	6,5	4,2	1,01	2,48	59,5	51,3	4,2	55,2	25,0	45,3
T 2	350 - 450	63,1	9,0	4,8	0,99	2,42	59,3	60,1	-3,0	62,4	24,6	39,4
	800 - 850	72,2	6,1	4,6	1,14	2,51	51,6	48,4	1,6	50,1	20,4	40,1
G 1	100 - 200	74,4	9,7	2,7	0,88	2,40	63,3	44,0	10,9	52,4	23,0	43,9
	400 - 500	66,5	8,9	2,0	0,89	2,42	63,4	55,3	3,3	60,1	28,7	47,7
	800	62,2	9,8	2,4	0,88	2,43	63,8	55,2	4,2	59,6	24,5	41,1
G 2	200 - 250	74,4	11,3	2,6	0,82	2,35	65,0	41,2	7,2	57,8	28,1	48,7
	550	58,7	12,8	4,8	0,77	2,32	66,8	59,9	0,8	66,0	24,2	36,6
	800	57,1	11,8	4,3	0,83	2,45	66,1	56,9	4,8	65,2	22,9	35,0

PV- pore volume; WV - water volume; AV - air volume; FC - field capacity; aFC - available field capacity

Table 8: Mean annual water balance of the restoration layers (years 2000 - 2010) (Berger 2012)

parameters [mm]	T 1	T 2	M 1	M 2	G 1	G 2	N 1	N 2
precipitation	653,1		620,5		662,4		631,3	
surface runoff	7,8	8,1	3,1	3,3	11,7	14,5	2,7	2,5
PET	665,6		654,0		678,6		753,3	
AET	478,2	493,9	491,6	486,0	519,6	510,2	558,3	558,7
seepage	165,3	148,9	122,2	127,8	122,4	130,7	61,8	61,2
ΔWg	1,8	2,2	3,5	3,3	8,8	7,0	8,4	8,9
field capacity	431	464	504	526	576	617	535	495
available field capacity	169	170	283	282	253	233	290	268

PET - Potential evapotranspiration; AET - Actual evapotranspiration; ΔWg - Change of soil water retention

Field capacity and available field capacity fulfil the requirements of the Landfill Ordinance (DepV 2012), the recommendations E 2-31 and E 2-32 of the German Geotechnical Society (GDA 2006; GDA 2010) and the uniform nationwide Quality Standards BQS 7-1 and BQS 7-2 (BQS 7-1 2011; BQS 7-2 2011). The field capacity reaches up to 500 to 610 mm and the available field capacity reaches up to 230 to 290 mm by using matured silt in the entire restoration layer. These values were also measured in ten years old recultivation layers!

4.3.5 Simulation of the water balance with the Landfill Model HELP

The Landfill Ordinance requires proofing the percolation rates. Such a simulation of the water balance can be carried out with the model HELP (Hydrologic Evaluation of Landfill Performance). This simulation was also done at the investigated recultivation layers (Berger 2012).

The simulations were performed with the meteorological data of the standard period 1961 to 2010 and also carried out with the data from 2000 to 2010. The decade 2000 to 2010 shows significant changes with respect to the factors that are particularly challenging to the effectiveness of a restoration layer. The first decade of this century shows significantly higher annual rainfall amounts (about 10%) and significantly higher mean annual temperatures (about 1°C) in all meteorological stations.

The calculated (decade 2000 to 2010) average annual seepage from the recultivation layer is located at the landfill site **N** at around 60 mm. The landfills **M** and **G** achieve average seepage of around 120 to 130 mm per year. The highest infiltration rates occur in landfill **T** with around 150 to 165 mm / a (Table 8). These simulation results are very surprising.

Field capacity and available field capacity are very high and on the landfills no seepage water processes from the recultivation layers were observed.
The matured dredged material with its high organic matter content seems not to behave like “ordinary” mineral soil. But the modelling approaches of HELP are based on “ordinary” mineral soils.

“Whether the water holding capacity of the dredged material is higher than the capacity modelled in HELP and thus the infiltration of HELP is slightly overrated, remains a speculation" (Berger 2012, p 8). Nevertheless the results clearly show the positive characteristics of the dredged material compared to marl. However, the question remains how ordinary substrates (soil types) should fulfil the requirements of the Landfill Ordinance. If we believe in the results of the HELP calculations even a substrate with extremely high field capacity and available field capacity seems not to be able to comply with the Landfill Ordinance.

In summary: matured dredged material (mixed soil and silt) meets in practice the soil physical requirements of the Landfill Ordinance.

5. Summary

In Mecklenburg-Vorpommern landfill sites are restored with matured dredged material since 15 years. This substrate comes from waterways and harbours. The used and tested dredged material originates from the port of Rostock, from the dredging of the waterways. This dredged material is classified, dewatered and processed in specially-developed inland disposal sites. Coarse components (gravel and sand) are used in the construction industry. The mixed soils are used in landscaping.

The organic-rich, silty and clayey substrates are used after dehydration and aging in recultivation layers of landfill sealing systems. The Rostock dredged material is not contaminated with pollutants.

The German Landfill Ordinance requires the proof of the water storage capacity (field capacity and available field capacity) for landfill recultivation layers. Whether the dredged material fulfils the demands of the Ordinance was examined on landfills already sealed with matured dredged material.

On four landfills, 2 to 15 years after their restoration, the chemical and physical status was determined (hydraulic conductivity, pore-size distribution, mechanical properties and chemical composition).

It could be demonstrated that the requirements of the Landfill Ordinance regarding field capacity and available field capacity are reliably observed even many years after the restoration. The use of matured dredged material (mixed soil and silt) in recultivation layers should be continued.

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