Proceedings of the South Baltic Conference on
Dredged Materials in Dike Construction
Rostock, 10-12 April 2014
ISBN: 978-3-86009-409-9
www.dredgdikes.eu

THE PROJECT DREDGDIKES: CHARCTERIZATION OF CHEMICAL PROPERTIES OF THE DREDGED MATERIAL AND FIRST RESULTS ON VEGETATION MONITORING

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Abstract. In the South Baltic cooperation project DredgDikes different dredged materials are investigated to be used in dike construction. In Rostock, focus is given to uncontaminated fine-grained organic dredged materials from the Warnow river delta, dewatered and ripened on the Hanseatic City of Rostock's containment areas. The treatment facility in Rostock only collects material which complies with the precautionary values of the German federal soil protection and contaminated site ordinance (BBodSchV, 1999) and thus is allowed to be reused. Three different dredged materials were analysed and a large-scale experimental dike has been built with different geosynthetics solutions. Coastal protection structures made of earth material have to possess a strong and close vegetation cover to reinforce the stability of dike constructions during flood events. Only this - maybe in connection with geosynthetic rolled erosion control products (RECPs) – offers protection against erosion and reduces the infiltration of water in the dike body. On both the dike and especially prepared testing plots the turf development on different dredged material surfaces and in different weather conditions has been investigated. In 2013 the cover ratio of vegetation was checked supported by aerial photos. During the overtopping events the photographic assessment of erosion damages on the turf before and after the single events was determined with photogrammetric and rectifying methods. For the evaluation of the root mass in the different cross sections samples were taken and prepared. In different cross sections drainage mats for load relieving were installed. They lead the leak water to tipping counters at the dike toe for discharge measurement. In samples taken the conductivity and the concentration of heavy metals as well as nitrogen and phosphorus were analysed. First results suggest that the use of uncontaminated dredged material in the dike constructions near the coast line is unproblematic regarding possible environmental effects.

Keywords: Dredged materials, dike construction, chemical characterisation, discharge of substances, vegetation development, rooting

1. Introduction

Since there are considerable amounts of dredged materials available along the Baltic Sea coast and dike construction materials such as limey marl or marsh clay are generally in short supply and need to be mined, often associated with heavy environmental impacts, the idea of using dredged materials in dike constructions is obvious. Even so the materials differ largely in their geotechnical and chemical characteristics and they may even be quite inhomogeneous, depending on the drying and processing methods.

According to the German Recycling Management Act (KrWG, 2012) - as dredged material is classified as waste - and other public laws, a possible reuse has to be proper and harmless (i.e. no deterioration of the public interest, particularly no accumulation of contaminants in the recycling process, §7 KrWG).

Due to their classification as waste materials and the associated difficulties for the planning process, there are only very few projects where these kinds of dredged materials have been installed as dike cover material (e.g. Bremischer Deichverband, 2013). Therefore, the project DredgDikes has been initiated by the University of Rostock, chair of Geotechnics and Coastal Engineering and Gdansk University of Technology, department of Geotechnics, Geology and Maritime Engineering to investigate possibilities to use different kinds of dredged materials in dike construction.

The Steinbeis Innovation Centre for Applied Landscape Planning in Rostock is responsible for the chemical and environmental analyses in the project. The focus in the present paper is set on the results achieved in Rostock, where a full-scale experimental dike has been built to investigate the different fine-grained materials. Geosynthetic reinforcement and rolled erosion control products (RECP) have been installed in some of the different cross-sections to improve the material behaviour. The test construction consists of two parallel dikes, one for seepage (East) and one for overflowing experiments (West), both of which can be filled with water to perform the experiments. There are different cross-sections, with varying slopes, with and without sand core, different geosynthetic solutions (for reinforcement and erosion control) and different dredged materials. An important aspect of coastal protection structures made of earthy materials regarding stability at flood events is the vegetation cover. It gives protection against breach and denudation as well as in part protection against moisture penetration.

All materials, matured (through physical and biological structure forming processes) on the drying fields of the Hanseatic City of Rostock's containment facilities, have been investigated in an extensive laboratory programme before installation and a monitoring programme has been planned in which the specific chemical parameters will be re-tested several times. The soil chemical investigations of the materials used during the construction period of the test dike mark the status quo and will be the reference level for all further investigation. Thus the discharge and dislocation of substances through leaching and erosion can be determined. These comparisons will permit to deduce the effective risk potential of dredged material. Also the turf development has been monitored from the day of seeding on and some additional experiments have been performed to compare the results on the dike surface. The vegetation and environmental analyses - not yet completed - should document the development of the dike seeding and its success. The conclusions of these analyses should be incorporated into the handbook, which still needs to be compiled.

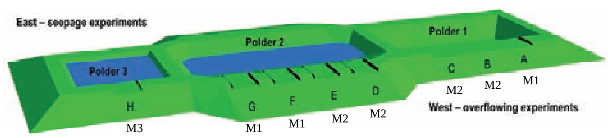


Fig 1. Rostock test dike with different cross-sections and applied materials

2. Chemical Characterization

2.1 Materials

The fine grained dredged materials used in the project (M1, M2, M3) are different sediments from dredging works and dried and processed on the municipality's containment facilities. Samples for the chemical characterisation were taken while emptying the containment polders (2006-2010) for a basis investigation. Before using the material for the test dike construction an investigation on soil mechanics was done. At the same time the sampling of single samples for TOC and grain-size distribution after removal of humus and carbonate was conducted to contain relatively homogeneous areas.

Further analysis was performed during the construction and after completion of the test dike. The samples were analyzed in a specialized laboratory. Up to the time of application the material achieved a friable structure and good manageability.

To offer dredged materials for reuse a detailed knowledge of the composition in the different storage heaps as well as their chemical characteristics are necessary. Based on the first investigations, different classes of comparably homogenous substrates were defined for different applications in the test dike (e.g. cover layer, sand core, homogenous cross-sections).

The materials investigated (M1, M2, M3) are fine-grained materials with high organic and lime contents. They come from the polder complex *Radelsee* of the municipality's containment facilities, where the sediments were sorted after the longitudinal flow method by grain size and organic matter content. The materials were built up to heaps for further maturing after an initial dewatering. The materials M1, M2 and M3 were partly applied with geosynhetic solutions in different parts of the test dike (cross sections A to H).

Previous to the dike construction a compaction testing field (M1 and M2 with a three-dimensional reinforcement mat in different depths) was built. This testing field is designed for further analyses which cannot be conducted non-destructively. Detailed Information to the construction of the compaction testing field and the test dike itself offer Cantré and Saathoff (2013). In polder 1 (cross sections B and C) as well as in polder 2 (section D to G) fittings for leachate with tipping counters for discharge measurement were installed. Samples of leachate were taken from each of these cross sections.

2.2 Methodology

The samples of the basis investigation were analysed to determine general geochemical parameters like pH, salt concentration, organic substance, lime content, as well as nutrients, heavy metals and organic contaminants.

The eluates of the materials were investigated to characterize the possible discharge behaviour or mobility of substances. Previous to the application in the test dike construction investigations on soil mechanics, TOC and granulation after humus and carbonate removal were performed in a specialised laboratory.

Another broad investigation of soil samples from the test dike will be performed in 2014 before the project finalises. Comparing the values at the time of construction with those after two years of precipitation, seepage, and overflowing will yield more knowledge about the materials' long-term behaviour. A long-term monitoring plan will be implemented.

Because no differences were expected the results from the basis investigation were used for the actual evaluation of hazardous substances. Accumulating leachate from the dike cross-sections was collected and analysed to determine the actual impact potential of the dredged materials used. In Winter 2012/2013 first leachate water was emitted through the drainage mats due to missing water absorption from the vegetation. The conductivity was measured once to twice a month. Once in a quarter a mixed sample was sent to a laboratory to determine the concentration of salt ions (chloride, sulfate, sodium). At the beginning of the discharge measures (January/February/March 2013) heavy metals, phosphorus, and nitrogen and at the end of the growing period (October/November 2013) only phosphorus and nitrogen were determined in the mixed samples.

At the compaction testing field the vertical leaching of salt ions (chloride, sulfate and sodium) was determined in the compacted soil (M1 and M2) in 2013 two years after construction. Therefore soil samples were taken with a drilling stick (Pürkhauer) at the soil horizon (1m) and from the single layers (0 to 25, 25 to 50, 50 to 75 and 75 to 100 cm below ground level) and were given to a laboratory.

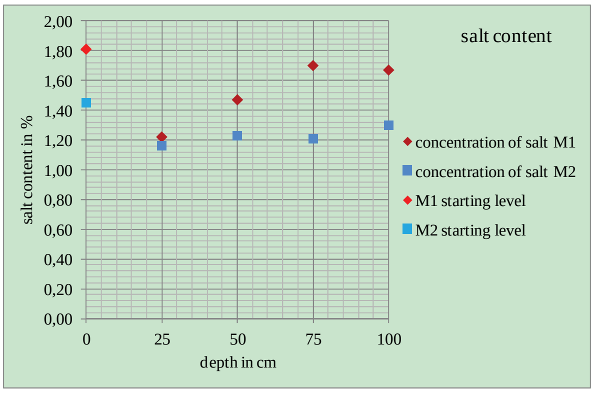
The chemical characterization were realized in compliance with the detailed requirements for sampling, analytics and quality management of dredged material from the Annex 1 German federal soil protection and contaminated site ordinance (BBodSchV, 1999). In view of the specifics of dredged material (origin, composition) additional determinations for sampling and application of analytical instructions were made. Due to the heterogeneity of the dredged material conditioned by the technological processes exclusively mixed samples per area were produced. For the investigation of grain-size being a main parameter in dredged materials the E DIN ISO 11 277: 06.94 (sample preparation through distribution of humus and carbonate) was conducted due to the high content of lime and organic matter for a real determination of sand, silt and clay in mineral fine grained soil.

2.3 Results

The results of the solid analysis are listed in table 1. No limit values were exceeded. The eluates of the materials were investigated as well to characterize the possible discharge behavior or the mobility of substances. As expected from the high sorption capacity and the neutral or slightly alkaline pH values, the mobility of heavy metals and organic contaminants in the materials are limited (Schachtschabel et al., 1989). The concentrations in the eluate are therefore usually in the range of the detection limit. Due to natural conditions - substrates from brackish water- high levels of salinity have been detected. Especially chloride is a very easily soluble and therefore leachable salt ion. Also, sulphate will deliver constantly from sulphur.

Table 1. Characterization of dredged materials M1 /2 /3 in comparison to the mean values of the municipality's containment facilities Rostock (IAA ∅) and the precautionary values of the BBodSchV (1999)

	unit	M1	M2	M3	IAA ∅	BBodSchV
pH value	[-log]	7.4 - 7.7	7.5 - 7.8	6.9 - 7.3	7.3	
Calcium carbonate	%	6.2 - 10.0	6.0 - 7.4	5.3 - 8.7	8.0	
TOC		5.0 - 6.2	4.7 - 6.0	2.2 - 3.2	6.5	
Salt concentration		1.8 - 2.2	1.5 - 1.7	1.2 - 1.8	1.9	
Magnesium	mg/100g silt	101 - 115	116 - 122	61 - 69	128	
Potassium		26 - 41	30 - 33	11 - 23	31.4	
Phosphorus		0.8 - 1.1	1.4 - 2.1	1.4 - 2.2	2.0	
Nmin		1.4 - 3.2	1.6 - 3.5	0.5 - 1	2.5	
Cation exchange cap.	mval/100g silt	27 - 32	25 - 26	16 - 23	26.1	
Lead	mg/100g silt	36	19	23	21.2	70
Cadmium		0.9	0.4	0.6	0.4	1
Chromium		20	16	13	35.2	60
Copper		36	23	22	22.4	40
Nickel		14.1	13	9.5	14.5	50
Mercury		0.57	0.28	0.37	0.3	0.5
Zinc		179	130	112	101	150
Arsenic		9.1	9.8	5.9	9.6	
Hydrocarbon		379	115	206	225	
PAH		1.5	0.89	1.4	0.9	3.0
PCB		0.028	0.015	0.01	0.033	0.05



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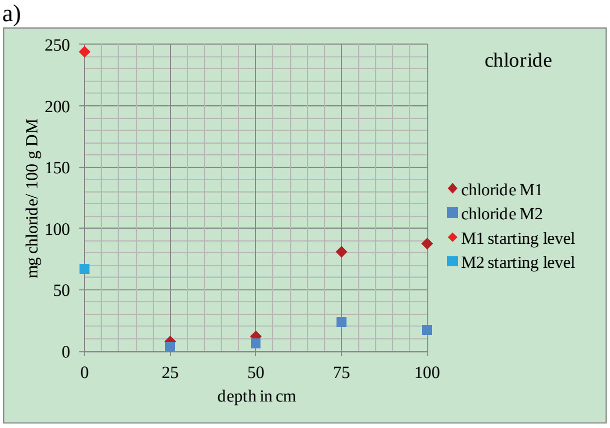

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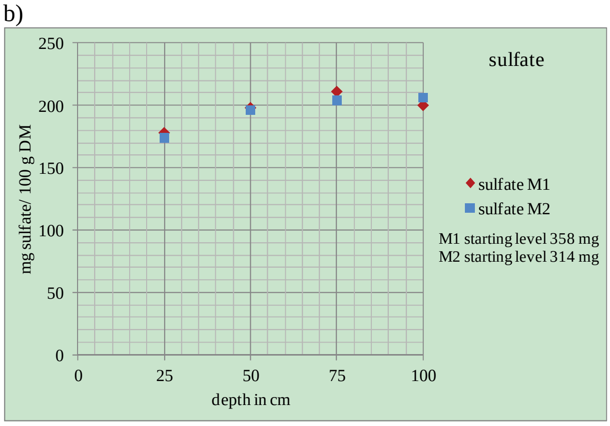

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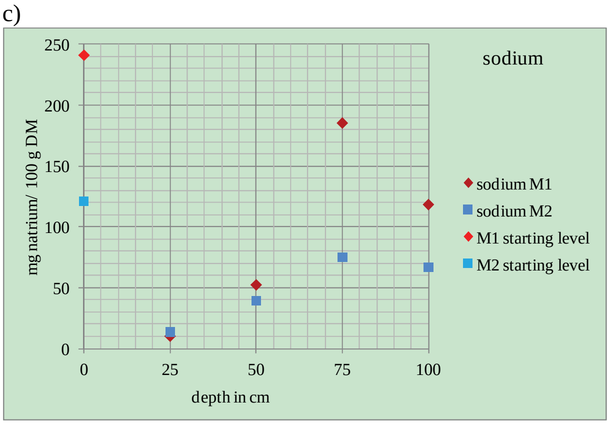


d)

Fig 2. a) to d) Content of salt ions in the different layers of the compaction testing field (M1 and M2)

The results of the investigation at the compaction testing field show a significant vertical leaching of salt ions in deeper layers during a period of one and a half year after construction. The distribution of the different salt ions is quite similar depending on the depth. As shown in the diagrams (Fig 2) there is a significant decline of chloride, sulfate and sodium concentrations in the topsoil. The highest concentration increase is in the layer 50 to 75 cm. In the layer 75 to 100 cm the concentration is lower; the maximum amount has not reached that depth yet. The chloride concentration is in the two top layers clearly beneath the base level. Chloride is a very soluble and fast washable salt ion. The content in both materials is almost completely washed away in materials M1 and M2 with natural precipitation. That the contents differ in the deeper layers result from the usually higher initial situation in M1.

The leaching began with increasing precipitation in the first half of January 2013 with cross section D, following E. The installed tipping counters measured the discharge after complete instrumentation. To show the differences in the leaching behaviour a period from mid March to the first filling within the seepage tests (Nitschke et al., 2014) was chosen for cumulating (Fig 3). With the beginning tests the measured leachate amount depends on which polder was filled.

The broken lines show the sections with erosion control and reinforcement solutions, the colors show different materials (red - M1, blue - M2). One can see that section C and E with geosynthetic solutions and cross section B (material M2) had a decreased leachate. Cross section F (M1) with geosynthetic solutions had the highest amount. The general assumption that sections with geosynthetic solutions decreases the rate of flow from the cover layer through a prevention of cracks could not affirmed within this period. Also that one material is far better than the other material could not proven (see section D Fig 3). The analyzed samples of the leachate are compared with the values of BBodSchV (1999) and the disposal ordinance (DepV, 2009) for orientation (Table 2). The requirements of the disposal ordinance for the restoration layer will enable an evaluation of the environmental impact from hazardous substances because of similar chemical requirements of this top layer. The limit values given in the regulations were only exceeded for conductivity; chloride and sulphate (compare DepV, 2009).

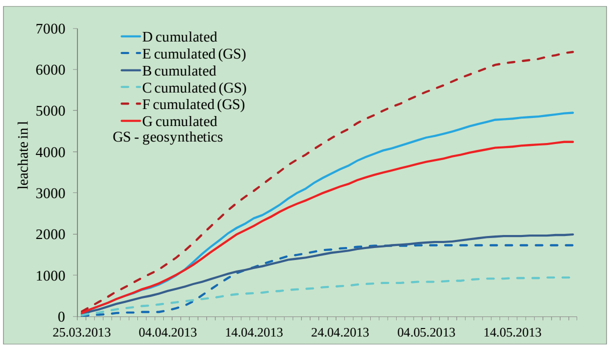


Fig 3. Cumulated leachate in different sections (M1- red, M2 - blue) period from end of March to the first filling

Table 2. Characterization of leachate from dredged materials M1 and M2 (values in average) compared to the inspection values of the federal soil and ordinance (BBodSchV, 1999) and the disposal ordinance (DepV, 2009)

Material		M2	M2	M2	M2	M1	M1	BBodSchV	DepV
Cross section		B	C*	D	E*	F*	G	Inspection value	Restoration layer
Quarter 2013		I - III	I - III	I - III	I - III	I - III	I - III	1999	2009
Conductivity	mS/cm	7.9	6.6	8.8	8.2	9.8	11.4		≤ 0.5
Chloride	mg/l	1508	957	1671	1523	1818	2798		≤ 10
Sulfate	mg/l	2328	2474	2635	2515	2536	3012		≤ 50
Sodium	mg/l	878	748	1009	958	1034	1646		
Quarter 2013		I	I	I	I	I	I		
Nitrogen	mg/l	3.03	5.19	6.61	7.24	n.a.	9.01		
Phosphorusus	µg/l	< 5	< 5	< 5	< 5	< 5	< 5		
Lead	µg/l	< 32	< 32	< 32	< 32	< 32	< 32	25	≤ 40
Cadmium	µg/l	bld	bld	bld	bld	bld	bld	5	≤ 2
Chromium	µg/l	6	4	1	12	1	bld	50	≤30
Copper	µg/l	bld	bld	bld	bld	bld	bld	50	≤ 50
Nickel	µg/l	bld	bld	bld	bld	bld	bld	50	≤ 50
Mercury	µg/l	< 0.25	< 0.25	< 0.25	< 0.25	< 0.25	< 0.25	1	≤ 0.2
Zinc	µg/l	10	bld	bld	bld	bld	bld	500	≤ 100
Arsenic	µg/l	2	3	4	< 2	4	2	10	≤ 10

bld – below limit of detection, n.a. – not allocable, * RECP – west and east – 3D geogrid

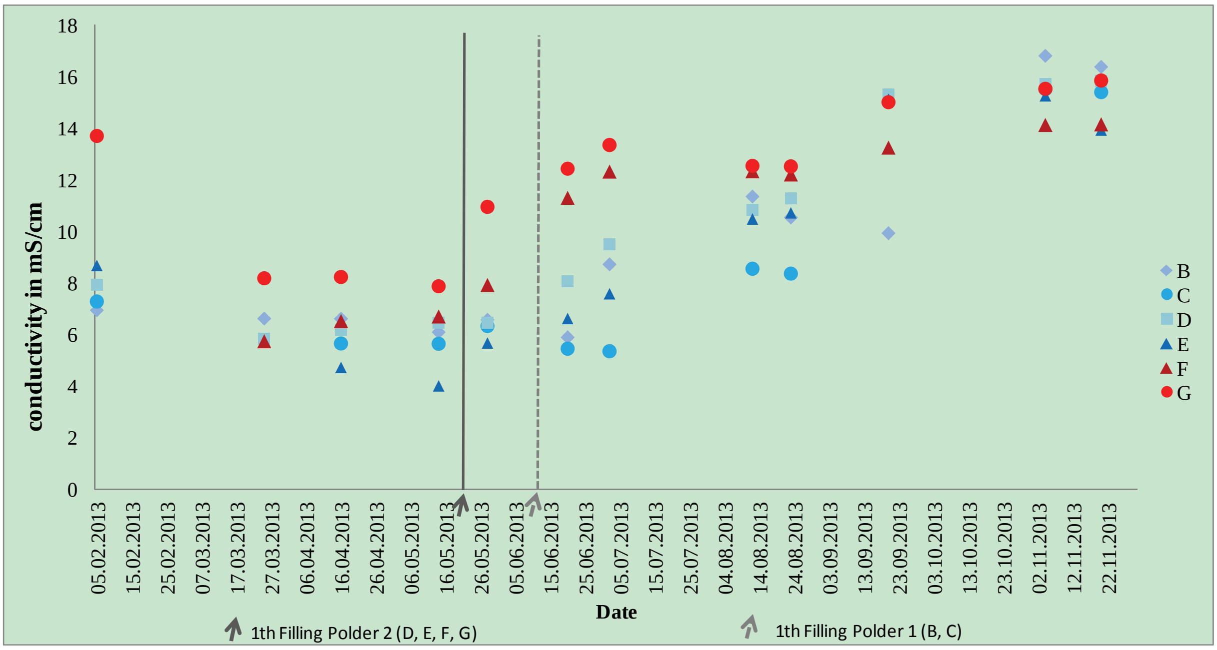
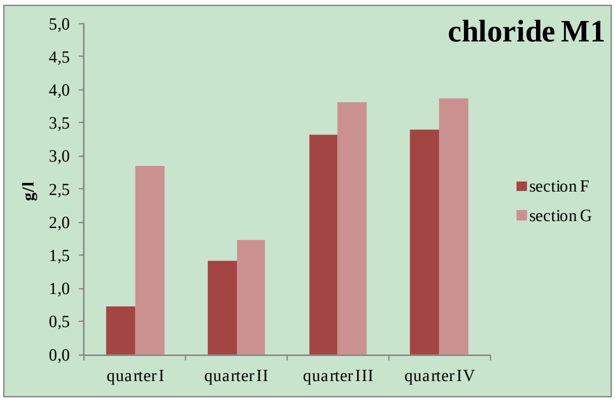


Fig 4. Conductivity in leachate from different cross sections (material M1 – red marks, material M2 – blue marks)

Due to the natural origin conditions of the dredged material (brackish sediments) in the leachate from the test dike high salt contents could be detected. The conductivity of the leachate increased with the filling of the polders, also depending on the brackish water used for filling (Fig 4).

The filling water (brackish water) from the ditches near the construction site had a conductivity of over 18 mS/cm. Chloride, sulfate and sodium were detected in high concentrations before and after the filling and overtopping experiments. Till September the polder were filled and emptied at different times. The graphics (Fig 5 to 7) show the contents in the sampled leachate in the 4 quarters of 2013. At the beginning of the discharge only through precipitation (January to March, Quarter I) high contents of chloride, sulfate and sodium were already detected in material M1 and M2 at which material M1 has the higher initial values in solid. Mostly the contents decreased in the period April to June (quarter II). The percolation through rainfall eased and the vegetation cover dehumidified the topsoil. In the end of May and the beginning of June the filling experiments started and in the following period from July to September (quarter III) a further increase was determined. This fact was expected because of the brackish water used for filling and the almost complete moisture penetration of the materials. Cross section G (material M1 without geosynthetic solutions, Fig 5a, 6a and 7a) shows a peculiarity with the high contents in quarter I. Already at the beginning of the investigations



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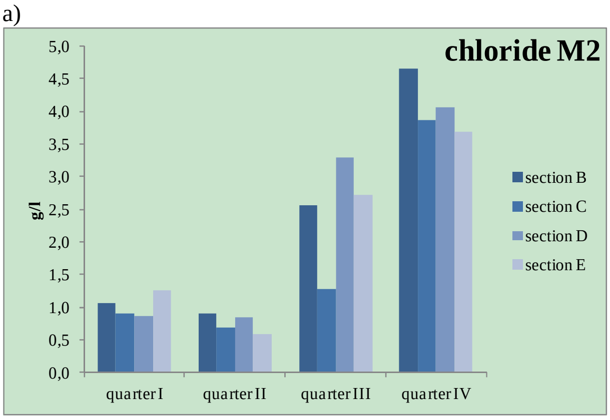
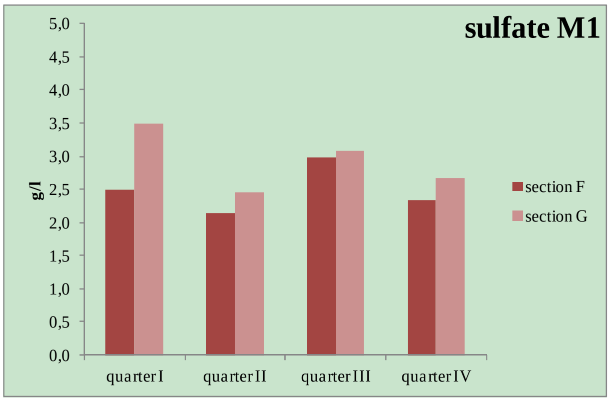


b)

Fig 5. Content of chloride in leachate a) material M1 b) M2



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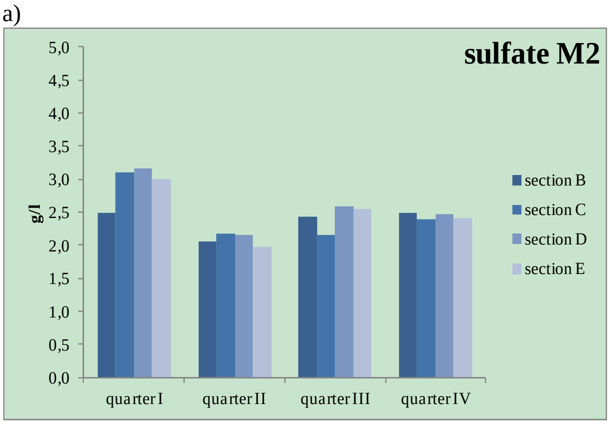


b)

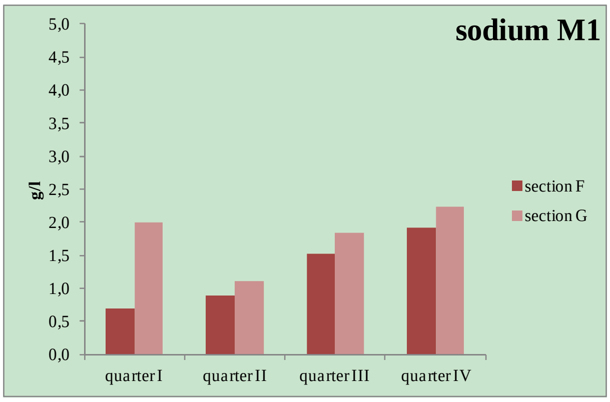
Fig 6. Content of sulfate in leachate a) material M1 b) M2

the concentrations of chloride and sodium were at a very high level. Maybe this result comes from the higher initial contents in material M1 and the increased cracking in this cross section at the beginning.

The content of sulfate (Fig 6) was at the highest stage in almost all sections in the first period and did not differ so much in the periods during the filling. Presumably the filling water with its variable composition is responsible for the difference in the salt ion contents.

The exemplary calculation (Table 3) of salt discharge only from precipitation (January to May) shows the high content of salt in the dredged material and illustrates the long-term impact for the environment through brackish sediments.

No high concentrations of heavy metals were detected and no limit value of the mentioned regulations was exceeded in the leachate (Fig 8, Table 2). Phosphorus and nitrogen were analyzed as well; also



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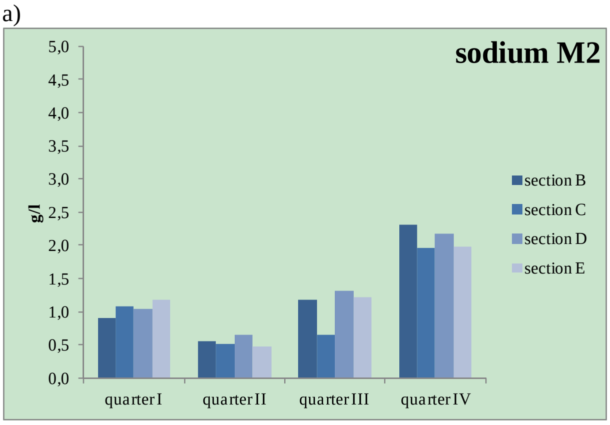

b)

Fig 7. Content of sodium in leachte a) material M1 b) M2

Table 3. Discharge of salt ions from leachate through precipitation (exemplary material M1 mid January to mid May, assuming that density 1 g/cm³ and layer thickness 1m)

	unit	Cl^-	SO_4^{2-}	Na^+
Content in dredged material in average	mg/100 g	244	358	241
	kg/ha	24400	35800	24100
Discharge with leachate	kg/ha	1270	2000	890
Percentage of feed charge	*%*	*5,2*	*5,6*	*3,7*

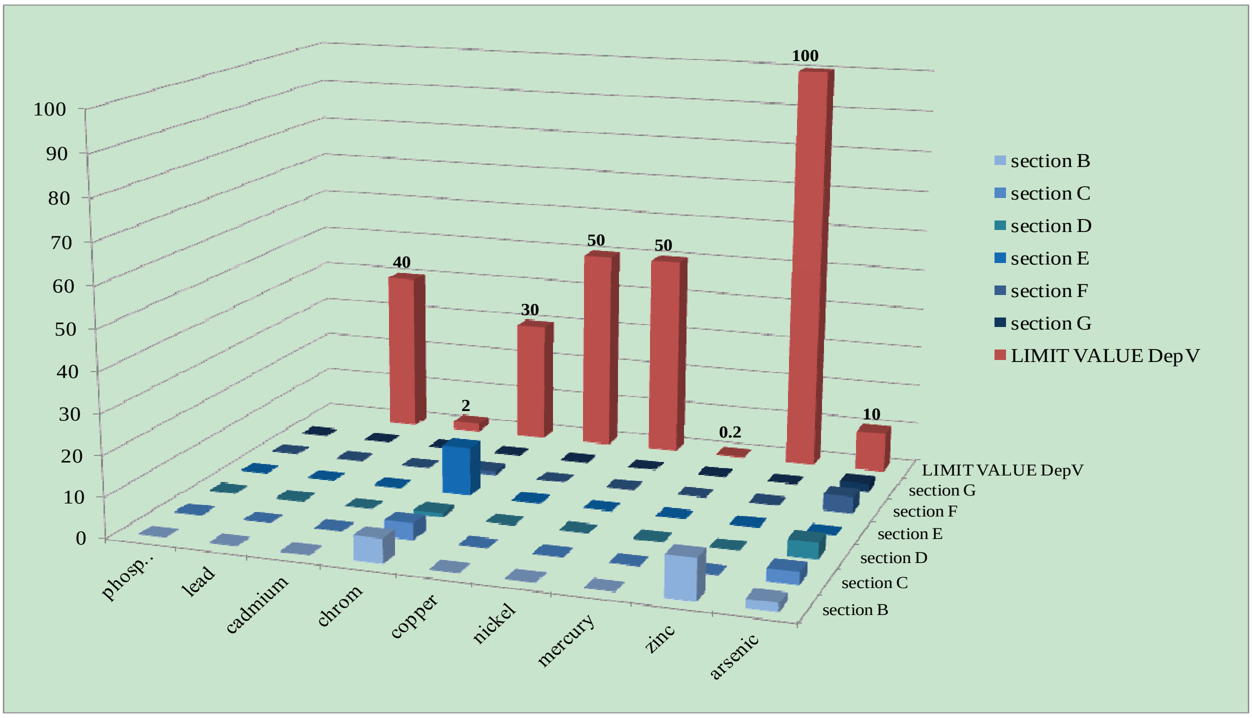

Fig 8. Heavy metal and phosphorus contents in leachate

there are no conspicuous concentrations. For example the content of nitrogen was significant below the limit value (50 mg/l) for endangered groundwater volumes of the groundwater ordinance (GrwV, 2010).

An occurring problem during the filling experiments was the strong iron clogging (iron hydroxide deposition) through the increasing discharge at the cross sections. The first deposition occurred at the tipping counter at cross section G. Afterwards also at cross section D. In late autumn this effect occurred also at the other cross sections but not to these extents. Through varying aeration and exclusion of air in the materials through the filling, it is presumed that, the iron hydroxide deposition emerged. At the cross sections without geo synthetics (B, D and G) the iron clogging appears to be larger. At present it is supposed that bacteria are responsible for the iron hydroxide deposition with decreasing temperatures and neutral pH values. The effects will be investigated this year to estimate the environmental impact and impacts on the stability of the dike itself (blinding of drainage).

3. Vegetation experiments and monitoring

3.1 Materials

The turf development both on the dike and especially prepared testing plots with different dredged material surfaces and with different weather conditions has been investigated.

The most important aspect for coastal protection structures made of earth material regarding stability at flood occurrence is the vegetation cover. The turf gives protection against erosion and also reduces moisture penetration. In preparation of the test dike sowing the seeding mixture (variation 1) was tested on all chosen materials directly on the storage heaps. Furthermore, the addition of legumes to a standard dike seeding mixture (variation 2) was tested. This seeding mixture with added legumes was also tested at the compaction testing field and following selected for the test dike seeding. The mixture with addition of legumes shall provide a further advantage for the surface strength and a fast greening. Moreover the white clover and the lucerne provide an additional nitrogen source and ensure the conservation through a fertilizing effect. On the test dike embankments the seeding mixture (variation 2) was tested in 27 small testing fields with different surface conditions, irrigation and wind protection on all chosen material. Table 4 gives an overview of the different seeding tests.

Table 4. Overview of seeding tests with number of test fields, material and reference period

Seeding pre-test 9 test fields M1/2/3 2011	Sowing in spring on fine, crumbly surface, irrigation directly after sowing
Compaction testing field 2 test fields M1/2 2011 - 2013	Sowing in autumn on compacted surface, loosened before seeding
Test dike n/a M1/2/3 2012 - 2013	Sowing in summer on compacted surface partly loosened or fine crumbly on erosion control mat
Seeding test on test dike embankment 27 test fields M1/2/3 2012 - 2013	Sowing in autumn on compacted surface or loosened or application of crumbly topsoil

Table 5. Seed mixtures for the test fields and the test dike

component	variation 1	variation 2
	[%]	
Festuca rubra	60	54.6
Lolium perenne	30	27.3
Poa pratensis	10	9.1
Trifolium repens		6
Medicago sativa		3
Sum	100	100

Two different seed mixtures variations were investigated in the seeding pre-tests. Variation 1 is a standard seed mixture for dikes. In variation 2 a portion of legumes was added: White Clover (*Trifolium repens*) and Lucerne (*Medicago sativa*). The composition of the seeding mixtures is presented in Table 5. The seeding was conducted with 30 g/m² after instruction. In variation 2 the portion of the principal constituents was reduced, respectively.

The seeding pre-tests confirmed the assumption of a fast germination and robust growth of grasses and grass-legume mixtures on dredged materials, which is based on long-term research experience (Henneberg, 1992). On both the compaction testing field and the test dike variation 2 was sown.

3.2 Methodology

Compaction testing field

After the construction of the compaction testing fields with three-dimensional reinforcement mat (herein after referred to as 3D-RM) against cracking (60 cm and/or 30 cm below ground) in September 2011 the surface of the two materials was roughened about 2 cm deep. The seeds was spread evenly, raked in and fixed with a roller (**Fig 9**). In October 2013 the root penetration at the compaction testing field was determined. For this purpose on the M1 and M2 fields 60 cm deep profiles were dug and the root penetration in the excavated material as well as at the profile walls were checked. Furthermore cracks were detected and documented photographically to assess the functionality of the 3D-RM.

Fig 9. Prepared compaction testing field

Test dike

The EAK (EAK, 2002/2007) recommend for a close turf at dikes a harrowing of the soil of 5 cm depth. The seeding should spread out with a spreader and rolled. Of advantage will be a donation of fertilizer at the beginning. The seeding should be conducted at adequate weather (not too wet, not too dry, no wind, soil temperature about 8°C).

Two weeks after construction of the test dike the sowing was realized in June 2012 by hydro-seeding. Therefore the seed mixture including the legumes was mixed with water and binder. Through the binder the seeds stick to the soil surface, however, on the steeper dike slopes (1:2) a slight slipping of seeds was noticed. The seeding could not be realised in conformity with the requirements of the EAK. The geometry of the test dike and the time factor demanded another procedure at this point. A starting fertilizer was avoided intentionally. At the test dike the mechanical mowing was chosen and realized as tending strategy. On one hand the mechanical mowing made sure that a thick and closed vegetation cover was established. On the other hand it is responsible for an increased growth of roots in the top layer of the soil and mostly didn't prevent the growth of weed (Kleber-Lerchbaum, 2008) and if so it could oust the seeded species. The mowing was done more often than usually on dikes in Mecklenburg-Pomerania (twice or thrice a year) because of the technical specifications of the mowing machine.

An additional seeding test (Seeding test embankments) was developed because of the considerable loss of seed from the dike surface. 27 plots of 1 m² with different boundary conditions were prepared to prove the suitability of the dredged materials for greening. The test fields were realized at the Eastern slopes of polders 2 and 3 on materials M1, M2, and M3 with different soil preparation and initial irrigation or wind protection.

In 2013 the vegetation cover of the test dike was checked twice with the help of aerial photos from a drone. The cover ratio and vitality were estimated and compared. Therefore the aerial photos were converted in raster images and a vegetation index in ArcGIS was calculated. The determined values were converted in qualitative values and afterwards classified. The 10 obtained classes (single color values in the raster) were summarized in 3 groups for a verbal interpretation of the vegetation cover. Whereas color value 1 to 5 means very good to good cover ratio, color value 6 means less covered areas and turf vitality not in a good state. And the third group covers the color values from 7 to 10 and labels the almost or totally bare areas of the dike. By counting the single pixels and the knowledge of the size of one pixel the cover ratio of the different groups can be calculated.

Through the classification the development status of the test dike in April and June could be compared. But it has to be said when comparing both images, that the lighting conditions as well as the mowing situation on the days the shots were made were not congruent.

Furthermore some installations on the dike were set up between April and June and were not removed from the raster image. Additional restrictions are related to the composition of the vegetation cover (leaves, stalks, branches, trunks etc.) and the reflection properties of the individual components. The background properties (reflection of the soil, leaf-litter covering), solar altitude angle and solar azimuth play also a role. Thus the graphs should be regarded as an approximation.

At the end of the vegetation period in the beginning of November and after performing the overtopping events soil samples from all embankments were taken. The samples were taken from the topsoil (up to 20 cm) for evaluation of the rooting in the overtopping areas from the dike top as well as from the upper and lower embankment. In total 48 samples were taken for evaluating the root penetration (cross section A to H). With a spade an earth clump was excavated and a sample of 5 x 5 x 15 cm was cut out (Fig 10a). The vegetation (grass cover) was cut (≤ 2 mm) and the sample was watered.

Afterwards the sample was sieved with a 1 mm sieve with water. The relatively intact root body (partly with stuck erosion product) was carefully washed out (Fig 10b) and fine roots with more than 1 cm length collected and separated. The strongly clotted rests of earth were sieved with water (analogue DIN 52098:2005-06) to remove organic rests (woody roots and debris) and small stones (Fig. 11).

The samples were dried to mass constancy at room temperature, weighed and stored for future treatment. A further step will be the ashing by 500°C in the muffle furnace for evaluating the ashless root mass. Conclusions for the comparison of the different materials and the effects of erosion products for the root development are expected.

The grass cover damages of the overtopping events at the test dike were documented. A comparison between the cross sections (material, RECP) and the overtopping (intensity, time) combined with the data of the root penetration analysis and the measures of the erosion rate (Olschewski et al., 2014) should enable a differentiation between the different materials and sections with erosion protection. The evaluation of the overtopping events is not finished yet. The single sections (60 x 60 cm) of each overflow channel were documented with a frame. The pictures were rectified and the concavity was eliminated by calibration with a special programme (image iron). With the double correction the pictures can be overlaid and the erosion can be clearly highlighted with the help of single sections.

Fig 10. a) Prepared sample for watering, b) Connected root system for further preparation

Fig 11. a) Soil and stones, rests of roots and organic material in the sieve, b) Washed out root system with rooted RECP

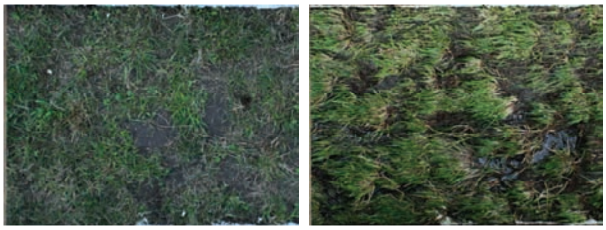

Fig 12. Cross section D (52 x 38 cm), flume 1, section 6, a) Initial situation b) After 4th overtopping

Fig 13. Cross section E (52 x 38 cm) with erosion mat, flume 1, section 6, a) Initial situation b) After 4th overtopping

The problem of comparing the different sections is to estimate the damages at the initial situation and after overtopping events (see Fig 12 and 13). A digitalization that will enable the estimation of damages is always a subjective procedure because there are no clearly visible edges. Other difficulties are the mowing rests at the beginning and the grass, which lie down due to the water flowing and partly covers the damages.

3.3 Results

Compaction testing field

The autumn sowing verified the spring results from the seeding pre-test. A fast sprout of the variation 2 mixture was observed. An adequate pre-winter growth provided a development of a vital and compact vegetation cover in the following vegetation period (**Fig 14**). The increased growth of the cultivars was documented by 4 necessary cuts in 2012. Between the two substrates M1 and M2 no significant growth differences could be observed. The amount of legumes was broadly similar in the first year after seeding, but in 2013 the amount of legumes was significant higher in M2 than in M1. Lesch (2012) made an analogue observation with these two materials.

Fig 14. Turf in September 2013 of the compaction testing fields a) Material M1 b) Material M2

Fig 15. Soil layer 20 to 30 cm, a) Material M1 b) Material M2

Fig 16. a) Rooted 3D-RM in material M2, b) Legume roots in depth of 50 cm in material M2

Fig 17. a) Material M1 soil horizon depth 60 cm (3D-RM), b) Material M2 3D-RM in 30 cm depth (visible rooting and cracking)

The excavation in October 2013 showed a rooting of the whole horizon (< 0.6 m). In material M1 the rooting clearly decreased below the first 30 cm depth. Also in the topsoil 0 to 30 cm of depth in M1 the amount of roots was clearly lower. Also few legumes roots were found in this horizon. This could be traced back to the fact of a low proportion of legumes (leaf area density) at the surface of M1. However, fine roots were also found in the layer of 60 cm. The root penetration in the topmost soil horizon of M2 was greater than in M1. The legumes roots reached a depth of more than 50 cm.

The contained 3D-RM attached against cracking had no negative effects on the root penetration, on the contrary, more roots were found on the geo grid, since roots can use the grid as water supply net.

Apparently the cracking could not be avoided by the 3D-RM. Above and beneath the 3D-RM cracks penetrated with branched roots could be observed. The width of the observed cracks differs from few mm to 2 cm.

Test dike

At the test dike the hydro-seeding failed at the beginning. After a first slight growth of grass an extensive saltbush (*Atriplex*) vegetation cover developed on parts of the test dike.

The continuous aridity led to a loss of germinating seed during the summer, covering only 20 % to 50 % of the area (Fig 18). The seeding and re-seeding of blank areas by hand in August didn't result in a complete vegetation cover before September. Only with significantly higher precipitation at the beginning of October and the reduced evaporation the growth of the grasses and legumes improved considerably (Fig 19a). The vegetation development in spring 2013 was inhibited by a long and strong winter. After the melting of the snow cover (till April) the young grasses in the re-sowing areas were visible. The grasses endured the winter quite well. In some areas the protective snow was blown away resulting in the freezing and death of the vegetation. The soil was dried by the dry freeze and the topsoil was like fine grained powder (the same situation as at the compaction testing field). The vegetation recovered with increasing temperatures in May and within some weeks a relatively close vegetation cover was established. (Fig 19b). However, with increasing temperatures the activity of voles rises (Fig 20a).

Fig 18. Surface of test dike two weeks after hydro-seeding, a) Decomposed binder b) Beginning saltbush growth

Fig 19. Turf development at the test dike a) polder 2 in 2012 b) polder 1 in 2013 freshly mowed (left)

Fig 20. a) Activity of voles and b) Crack at the test dike

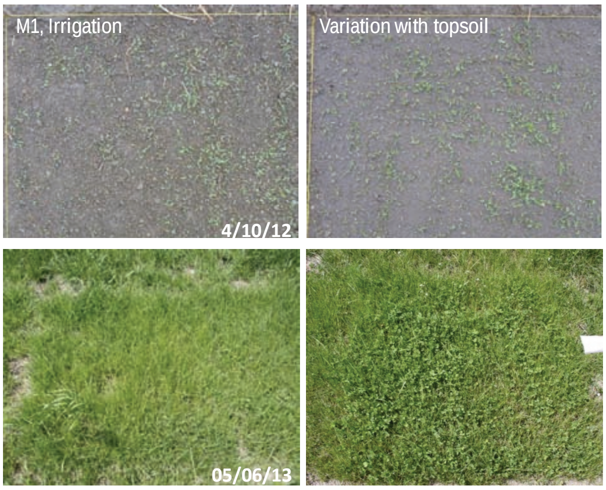

Fig 21. Two different variations of the seeding test on the dike embankment – compacted surface material M1 with initial irrigation (left) and variation with topsoil (2 cm) above dredged material M2 (right)

Test dike embankments

The tests were installed in mid-September 2012 resulting in a fast and regular greening. Only marginal differences between the variations could be observed: the vegetation cover in the variations with topsoil germinated quicker and looked a bit more compact than with dredged material on the top 4 cm. The fields were monitored in 2013 too. The differences in compactness were even more insignificant only the amount of legumes in the topsoil variation was higher than in the other variations (Fig 21).

The whole vegetation cover of the test dike was checked twice with the help of aerial photos from a drone. The cover ratio and vitality were estimated and compared. In April after the winter up to 64% of the areas were covered with vegetation in a good state. In June with recovered vegetation 80 % of the areas achieved a good cover ratio. Some areas were still not complete covered till June for example the eastern slope. Here, especially, seeding problems were patent. The slope had little vegetation from the seeding and was covered very fast by the saltbush (*Atriplex*). In winter the saltbush died back. Despite of re-sowing some areas were still bare in June (Fig 22).

The evaluation of the erosion damages by overflowing is still under examination. Further experiments will conducted this year. So here the effects only at two samples should be viewed in detail.

The turf and the network of roots of the different embankments (cross section B to H) have borne up against the overtopping experiments, so far. A complete functional failure of the slope could not be detected. Single grass blades of the turf were pulled through high traction from the overflowing water. Apart from that, areas without vegetation cover were eroded. The highest concentration of roots shows the first third of a cover. The consequence of erosion is the reduction of the protective effect. In the areas with no vegetation cover the surface is exposed to hydrodynamic impacts and the erosion progresses in depth (Vavrina, 2010). The fine grained soil particles were eroded through overflowing water till the network of roots beneath lay open. Soil particles were partly washed out of the roots. If the highly branched root system of young fine elastic roots remains intact than it will resist till the highest loading increment so far. After the first overtopping almost only the bare areas were visible when the mowing rests and dry grass vanished. Fig 23a shows a vole hole surrounded by a nearly intact vegetation cover. The highest investigated loading increment so far with 4 overtopping events and a maximum flow velocity of 3.52 m/s (maximum water height 0.1 m) showed no grave damages at this point (Fig 23b).

Fig 22. Comparison of cover ratio of the test dike after winter season in April (left) and mid June (right) 2013 (basis aerial photo Professorship of Geodesy and Geoinformatics)

Fig 23. Detail cross section D, a) Initial situation (bare areas and vole hole) b) 4th overtopping

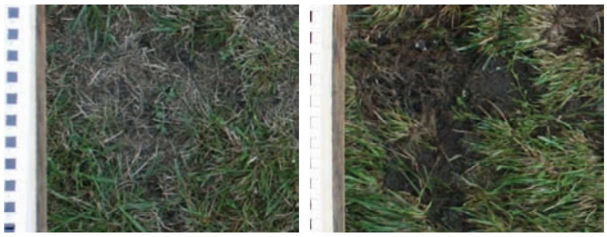

Fig 24. a) Detail E (initial situation with dry vegetation) b) 4th overtopping (fine networking roots visible in RECP)

Fig 24b shows very pronounced surface erosion in cross section E, where RECP was used in a depth of 4 cm. The turf was damaged before the experiments started, dry grass blades can be seen (Fig 24a). The loose soil above the RECP (no compaction) was washed out in spite of the branched root system. Already after the first overtopping event the cover showed damages. With the further overflowing the area eroded more and more and consequently the RECP with contained roots lay bare.

The previous optical evaluation of two samples with the same material (M2, with and without erosion mat) showed differences in the eroded areas. It looked like that the RECP increased the erosion. Partly the turf looked like peeled off. The RECP was applied after the final compaction of the dike surface and was covered with dredged material. The material crumbled only loosely on the RECPs. Because of the loose packing at the surface the roots grew at first along the RECPs and rooted only slowly into deeper layers. In spring 2014 further experiments at the test dike are planned. A concept envisaged is to check the resistance of the slope through fast opening and shutting of the sheets. These forces shall simulate a kind of wave overflow.

4. Discussion

Environmental relevance of the chemical analysis

The determined values of heavy metals in leachate do not constitute a potential risk of the different protective subjects' soil, plants or animals. They are below the limit values of different regulations as also are the values in the solid. Heavy metals and organic contaminants are chemically stable and heavily available. Reversing conditions (reduction – oxidation) could invert this status and the contained heavy metals could be available, e.g. within the first weeks of drying freshly dredged materials. Then the leachability decreases subsequently (Stephens et al., 2001).

A discharge of heavy metals or the nutrients nitrogen and phosphorus could not be detected in the leachate. In contrast to heavy metals there is an oversupply of nutrients and salt. According to agricultural aspects the nutrients magnesium, potassium and calcium are at a high level of supply for plants (Düngung, 2004). If the vegetation can't absorb these nutrients they will be subject to leaching processes.

The salt ions behave likewise. First of all chloride is a very soluble salt ion and therefore easily washed out in short term. In the leachate very high values of chloride, sulfate and sodium were determined. There is evidence to suggest that also the nutrients magnesium, potassium and calcium could be determined in high concentrations. Over 10 years corresponding results provided the lysimeter experiments with dredged material for soil improvement (Henneberg and Neumann, 2011). The exemplary calculation of the discharge of chloride, sulfate and sodium showed that in 4 month 3 to 5 % of the initial content is washed out. Experiences from the lysimeter experiments (dredged material mixed with topsoil) showed analogical results. After 10 years all of the original chloride and about 60 % of the original sodium amount were gone, though sulfate will be washed out constantly for another ten years at least. On the contrary in this experiment it was also proven that phosphorus and nitrogen will not discharge in great amounts from dredged material (compared with topsoil variations).

All in all it therefore becomes clear that the common inorganic contaminants contained in the dredged material don't violate the requirements of the mentioned ordinances, but it is the discharge of salt ions that could be problematic for the environment (Henneberg and Neumann, 2011; Gebert et al., 2010).

These previous scientific findings indicate that the discharge of salt has to be monitored when dredged material is used. Normally the fine grained dredged material with high content of organic matter can store a large part of the natural precipitation which is useful for the plants (Henneberg and Neumann, 2011; Morscheck and Henneberg, 2012). If the dredged material is saturated with water (e.g. because of increasing precipitation, loss of impermeability) and there is no removal by the vegetation, the excess water is discharged and with it also salt and nutrients. Despite of the salt and nutrients dislocation with the leachate a potential risk exists by the dislocation from the dike surface due to damages on the vegetation that allows erosion to transport soil particles.

For dike constructions with comparable dredged material the knowledge of the setting, e.g. construction site or subjects of protection is important. An endangerment of soil and groundwater should be avoided. Consequently dikes with dredged material from brackish sediments should only be built near the coastline and it should be ensured that the leachate is canalized almost directly into the Baltic Sea.

Apart from the salt there is another uncertain issue. The iron hydroxide deposition at the drainage and the dike toes through repeated filling could arouse public concern. It is not sure whether the iron clogging will appear at the other dike projects (e.g. pilot dike) to this extent. But to get the acceptance of the general public they should be informed comprehensively. In the first instance this effect and related environmental issues should be thoroughly investigated.

Vegetation issues

Within one year a good turf (about 80 % cover ratio with vegetation in good conditions) grew on the dike.

After initial difficulties during the germination (reseeding) and increasing growth of weed the dike showed a relatively close and green vegetation cover.

The so far considered soil horizons at the compaction testing field for comparison purposes (sowing in 2011) showed in both materials M1 and M2 a good and relatively thick rooting of the first 20 cm. Also in the deeper layers a networked root system was observed, the rooting covered the whole horizon ($\geq$ 60 cm). Especially in material M2 the legumes with their strong roots penetrated also the deeper layers. The shallow dredged material layer achieved in that time due to shrinkage and bulking, frost and animal activity as well as rooting a clear structure/texturing. Through these processes the impermeability increased gradually since the development also went on in the depth (compare Gebert et al., 2010). Rooting in an overcompacted soil rich in clay needs adequate pore and aggregate formation (Hartge, 1985). The loose topsoil with its fine distribution of aggregates contains the higher root density, too. The root density decreases with increasing depth and compaction of the soil (Vavrina, 2010).

The used 3D-RM to avoid cracks did not have a detectable effect on the cracking and the rooting at the investigated areas of the compaction testing field so far. Other measures have to be investigate whether a further maturing of the materials or a deepened surface preparation etc. would help to avoid the cracking. In spite of the compaction there were enough cavities for root growth in the depth. The water supply was adequate whereby the geosynthetics worked partly as pathways. The investigation of the vertical leaching of salts revealed that a percolation and therefore a relative permeability exist at the compaction testing fields.

Also the test dike will be used to determine whether the geogrid attached for reinforcement and against cracking could at least influence the cracking amount and dimension. Therefore excavations will be realized at the end of the project. Smaller and finer cracks could also be sealed by the mentioned processes of structure forming and thereby increase the impermeability again. A serious permeability problem is animal activity (vole) at dike cover layers. The vole proliferates very fast. Raptors or rodenticides did not work. A regularly pasturing with sheep which seals the holes again or a plugging with dredged material could not be realized. From this point of view a cursory glance at material M3 showed good qualities regarding greening in short term, compaction and the decreased cracking, hitherto.

The previous evaluation of the erosion defects in samples with the same material (M2, with and without RECP) showed differences. It looked like that the erosion mat increased the erosion. Maybe on the surface of the erosion mats shear forces benefit the formation of shear joints. Further evaluations will take place. It remains to be seen how the sections will bear up with increasing loads.

The earth volume samples from the test dike showed a strong but differentiable rooting in the near-surface layer (0 – 20 cm). The comparison of the root mass in still to be conducted investigations shall offer further results for the different materials and the use of erosion mats in the cross sections.

At the end of this project the different requirements of sea dikes and river dikes constructions have to be confronted with the requirements that dredged material could really fulfill and the possible environmental impact.

5. Summary

1. In compacted cover layers of dredged material a vertical leaching of salt ions can be detected. The discharge of chloride, sulfate and sodium continued gradually.
2. The amount of leachate increases with increasing penetrating precipitation and decreasing abstraction of water by plants. Also the amount of leachate increases with load by filling.
3. The concentration of salt ions is very high in the leachate from dredged materials. Heavy metals, phosphorus and nitrogen are not detected in high concentration. By repeated filling the iron hydroxide deposition at the drainage increases.
4. The placing of dike constructions with dredged material has to be conducted under defined specifications to avoid environmental impacts on ground water and soil by possible discharge of salt.
5. A good greening of the dredged material at dike construction is proven by compliance with the frame conditions, e.g. preparation of surface and date of sowing.
6. At the whole dike as well as the compaction testing field cracks could be observed. 3D-RM does not have a visible effect on cracking and rooting in the investigated areas of the compaction testing fields.
7. At the test dike material M3 showed the best status by fast greening and reduced cracking at the first glance.
8. The whole soil horizons ($\geq$ 60 cm) of the compaction testing fields with material M1 and M2 were rooted. In material M2 more legume roots and a higher density of roots were detected.

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