FINE-GRAINED ORGANIC DREDGED MATERIALS FOR DIKE COVER LAYERS – MATERIAL CHARACTERISATION AND EXPERIMENTAL RESULTS

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Abstract: In the South Baltic cooperation project DredgDikes different dredged materials are investigated to be used in dike construction. Depending on the type of dredged material combinations with different geosynthetic solutions and composites from dredged materials and ashes are tested. The investigations are mainly performed in Rostock and Gdansk. 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. Therefore a considerable geotechnical and chemical laboratory programme has been performed for material characterisation and a large-scale experimental dike has been built. The dike with a height of 3.30 m consists of ten different cross-sections with three different dredged materials, different geosynthetics solutions, and varying slope inclination. Since the dredged materials possess high natural water contents even after the ripening process, they tend to considerable shrinkage, which is why geosynthetic reinforcement has been placed in parts of the dike cover layers to reduce cracking. Also geosynthetic erosion control products have been installed at parts of the surface to reinforce the roots of the turf and thus to strengthen the whole construction with respect to surface erosion. The construction can be filled with water for seepage investigations and some sections are prepared for overflowing experiments to test crest and landside slope with respect to erosion stability. Additional laboratory tests have been performed of which an overflowing test is presented in more detail. Both on the dike and on especially prepared testing plots the turf development on different dredged material surfaces and in different weather conditions has been investigated. The first results have been summarised here. Apart from general problems on the construction site in the very wet summer of 2011, the installation of the dredged material in the experimental dike was unproblematic. Different compaction approaches have been examined and the results are presented here.

Keywords: Dredged materials, dike construction, chemical characterisation, geotechnical characterisation, installation, grass development

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1. INTRODUCTION

The main goal of the project DredgDikes is to investigate possibilities to use different kinds of dredged materials in dike construction. At European, federal and state level, there is consensus that the onshore accommodation, storing, preparation and beneficial use is subject to waste regulations, as dredged material is classified as waste. According to its material composition it is a waste for disposal or waste for beneficial use. According to the German Recycling Management Act (KrWG, 2012) 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). However, there is no explicit regulation to soil conservation or waste law, tailored for the reuse of dredged materials in dike construction yet. The existing soil conservation and waste regulations only allow a restricted definition of contaminant limits for the use of dredged materials. The use of dredged materials in dike construction is only possible in specific individual cases (compare EAK, 2002/2007). Due to the lack of a legal basis, the classification according to the German federal soil protection and contaminated site ordinance (BBodSchV, 1999) is generally possible so that particularly fine-grained organic dredged materials may be used if they comply to substrate-specific precautionary values for soil (annex 2 BBodSchV, 1999). However, 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). 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 short and need to be mined, often associated with heavy environmental impacts, the idea of using the dredged materials in dike constructions is obvious; although the materials differ largely in their geotechnical characteristics and they may even be quite inhomogeneous, depending on the drying and processing methods.

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. The Steinbeis centre for Applied Landscape Planning, Rostock is responsible for chemical and environmental analyses in the project. Two more partners are responsible for large investments and 15 associated organisations help in discussions, decision making, providing materials, and with the dissemination of the results. In the project two approaches are followed: In Rostock, fine-grained dredged materials from the Warnow river mouth are investigated. Because of their high natural water content even after ripening, shrinkage and cracking is a major problem, which is why geosynthetic reinforcement has been included in the investigations. To enhance the erosion stability of the materials also in a partial or un-vegetated state, erosion control mats have been applied. In Gdansk, fine dredged sand was mixed with different ashes to get reliable composite materials to build both the sand core and cover layer of dikes (Sikora and Ossowski, 2013).

The focus in the present paper is set on the results derived in Rostock, where a full-scale experimental dike has been built to investigate the different fine-grained materials, ripened on the drying fields of the Hanseatic City of Rostock's containment facilities (figure 1). Geosynthetic reinforcement and erosion control products 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), which can be performed by filling the polders with water. There are ten different cross-sections, with varying slopes, with and without sand core, different geosynthetics solutions and different dredged materials. The results will be compared to those derived in other dredged material and/ or dike cover related projects (Gröngröft et al., 2005; Van der Meer et al., 2010; Hoffmans, 2012; Beyer et al. 2012). All materials used in the test dike have been investigated in a considerable laboratory programme before installation and a large monitoring programme has been planned in which the specific chemical and geotechnical parameters will be re-tested several times. Also the turf development has been monitored from the day of seeding and some additional experiments have been performed to compare the results on the dike surface.

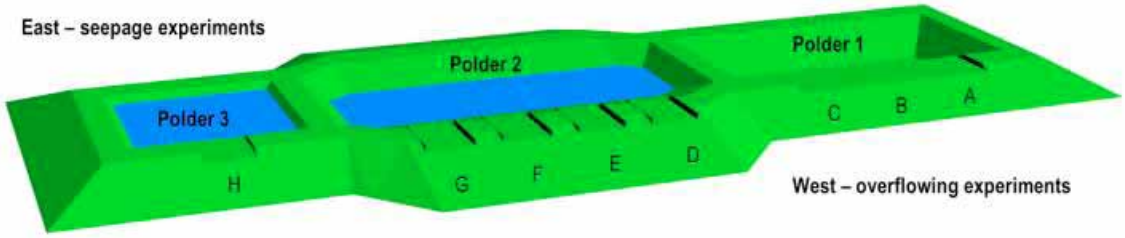


Figure 1. Three-dimensional model of the Rostock DredgDikes test dike (Cantré and Saathoff, 2013)

2. CHARACTERISATION OF THE DREDGED MATERIALS USED

The fine grained dredged materials used in the project (M1, M2, M3) are different sediments from frequent dredging works in coastal waterways and harbour facilities in the Warnow river delta in Rostock (Baltic Sea coast). The substrates are dried and processed on the municipality's containment facilities. The materials investigated are fine-grained materials with high organic and lime contents. They come from the polder complex *Radelsee*, where the sediments were sorted for grain sizes and organic matter content after the longitudinal flow method. After an initial dewatering the materials were build up to heaps for further ripening.
General geochemical parameters like pH, salt concentration, organic substance, lime content, as well as nutrients, heavy metals and organic contaminants in the dredged materials have been determined while the materials were removed from the containment polders between 2006 and 2010. Also the grain-size distribution was determined after removal of humus and carbonate. Before the application in the test dike construction an investigation on soil mechanics, TOC and granulation after humus and carbonate removal was performed. Based on this investigation, different classes of comparably homogenous substrates were defined for different applications in the test dike (e.g. cover layer, sand core, homogenous cross-sections). Further analysis was performed during the construction and after completion of the test dike.

2.1 Chemical Characterisation

Samples for the chemical characterisation were taken both while emptying the containment polders (2006-2010) and during construction of the test dike (2012). The samples were given to a specialised laboratory. For the evaluation of hazardous substances the results from the basis investigation were used. In the time of three to six years no differences were expected. Another investigation of soil samples from the test dike will be performed in 2014 when the project will finalise, to be used for a broader evaluation, comparing the values at the point of construction with those after two years of precipitation, seepage, and overflowing. However, a long-term monitoring plan will be implemented to gain even more knowledge about the materials' long-term behaviour.
Also, the eluates of the materials were investigated to characterize the possible discharge behaviour or 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. The results of all analyses are collected in table 1. 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. Accumulating leachate from the dike cross-sections will be collected and analysed to determine the actual impact potential of the dredged materials used.

Table 1. Characterization of dredged materials M1 /2 /3 in comparison to the mean values of the industrial silt processing facility 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	127.8	
Potassium		26 - 41	30 - 33	11 - 23	31.4	
Phosphor		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	25.5 - 25.9	15.5 - 22.5	26.1	
Lead	mg/100g silt	36.0	19.0	23.0	21.2	70
Cadmium		0.9	0.4	0.6	0.4	1
Chromium		20.0	16.0	13.0	35.2	60
Copper		36.0	23.0	22.0	22.4	40
Nickel		14.1	13.0	9.5	14.5	50
Mercury		0.57	0.28	0.37	0.3	0.5
Zinc		179.0	130.0	112	100.5	150
Arsenic		9.1	9.8	5.9	9.6	
Hydrocarbon		379.0	115.0	206.0	225.3	
PAH		1.5	0.89	1.4	0.9	3.0
PCB		0.028	0.015	0.01	0.033	0.05

2.2 Geotechnical Characterisation

The geotechnical characterization was performed according to German DIN-standards for soil and soil mechanical analyses. For materials M1 and M2 three subsamples were taken respectively. The results of the analyses are summarised in tables 2 and 3, the latter showing only preliminary results, because during the analysis, different problems in determining the standard geotechnical parameters emerged, which will be addressed in detail.

The fine-grained dredged materials are mainly characterized by high water-, organic-, and lime-content, which have considerable influence on other geotechnical parameters. The organic content affects the grain-size distribution because of the agglomeration of organic and fine-grained mineral particles. In a standard sieving and hydrometer analysis after DIN 18123 the fine particles relocate to the coarse fractions and thus cannot be determined (figure 2). By destroying the organic and lime content with hydrochloric acid and hydrogen peroxide (e.g. after DIN ISO 11277) the agglomeration can mostly be broken and a realistic result of the content of fines can be obtained.

Table 2. Reliable results of the geotechnical analysis

Sample	standard	M1	M2	M3
Water content w [%]	DIN 18121	61 - 68	55 - 73	46
Organic matter OM [%]	DIN ISO 10694	10 - 11	9 - 10	6
Lime content LC [%]	DIN 18129	9 - 10	8	10
Initial shear strength c_u [kPa]	after DIN 4094	53-132	19 - 34	120
Angle of friction φ [°]	DIN 18137	28 - 30	28 - 31	30
Cohesion c [kN/m²]	DIN 18137	35 - 47	13 - 19	59

Table 3. Preliminary results of the geotechnical analysis for further examination

Sample	standard	M1	M2	M3
Liquid limit LL[%]	DIN 18122	80 - 98	64 - 88	52 - 57
Plastic limit PL [%]	DIN 18122	75 - 81	54 - 67	49 - 54
Shrinkage limit SL [%]	DIN 18122	58	42 - 47	51
Plasticity index PI [%]	DIN 18122	4 - 22	11 - 24	3 - 4
Consistency index CI [-]	DIN 18122	2 - 5	0 - 1	2 - 4
Optimum water content w_{opt} [%]	DIN 18127	40 - 43	32 - 35	31
Proctor’s density OD [g/cm³]	DIN 18127	1,1-1,2	1,3	1,4
Water permeability k_f [m/s]	DIN 18130	4E-09	5E-10	1E-08

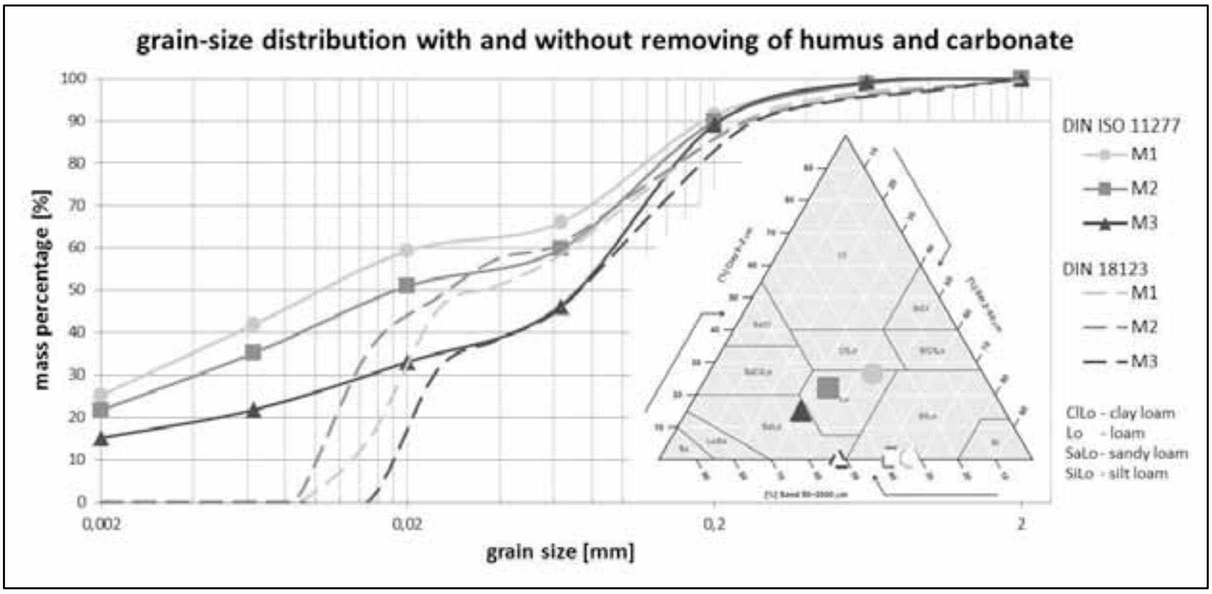


Figure 2. Grain-size distributions with and without removing of humus and carbonate and USDA triangle

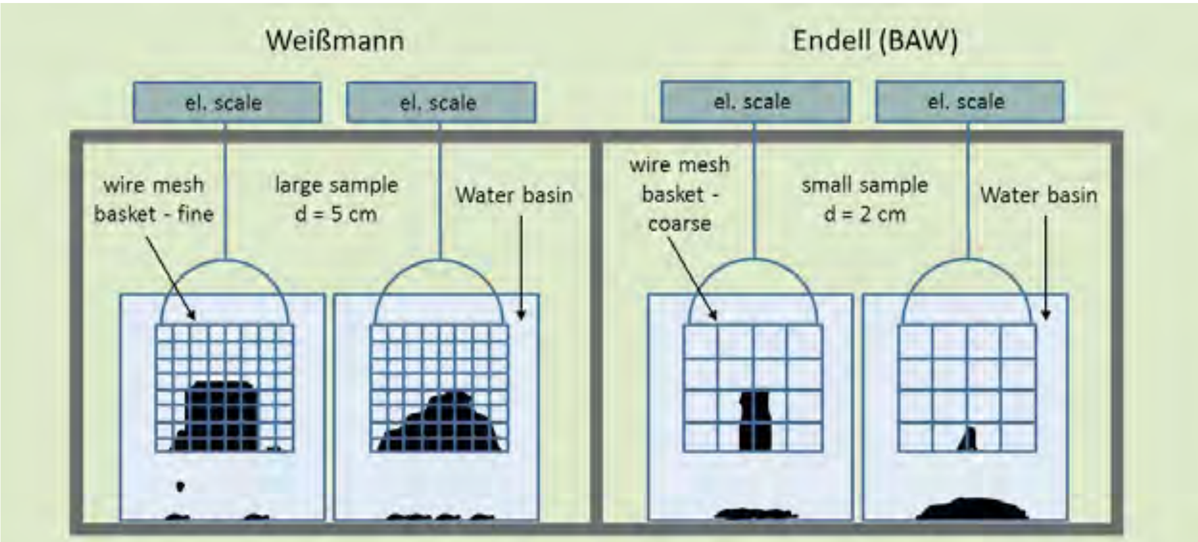
The large amount of fines also causes high water binding capacities. The natural water contents of the fine-grained materials M1 and M2 are very high and very similar in spite of their different ripening (drying) time. Material M1 (ripened for 5 years at the time of laboratory testing) is more homogenous than material M2 (ripened for 2 years), also showing considerable differences among the subsamples (e.g. w = 55...73 %). There is also a considerable difference between the initial shear strength of the two materials, although there are only marginal differences in grain-size distribution and water content.

The results of plasticity, Proctor's density and water permeability have to be interpreted with carefully since they are influenced by the organic content. The determination of the plastic limit is problematic, because the material started to flake before reaching the 3 mm plastic limit which is why the applicability of the Cone Penetrometer Method (DIN ISO/TS 17892-12) is being investigated for the determination of both the liquid and the plastic limit of these kinds of materials (compare Campbell et al. 1979, Azadi, Monfared 2012).

Also, the drying procedure for the compaction test has to be defined for dredged materials. The German standard DIN 18127defines a temperature below 60 °C to dry organic soils before re-wetting (which is vague) and the material should be dried down to a water content between shrinkage and plastic limit. Preliminary tests have shown that there are differences in the compaction results when completely drying at 55 °C, completely air drying and air drying down to a water content of 25 % (Große and Saathoff, 2013).

The results of the water permeability were obtained at 400 kPa cell pressure and 50 kPa loading, which were both applied quickly before starting the saturation. The authors assume that the samples were compressed during the quick application of the cell pressure which may result in a lower permeability. Presently the dependencies of saturation stepping and load state on the determined permeabilities are investigated.

Apart from the standardized geotechnical parameters, the erosion resistance of a dike cover material is of particular interest. Decomposition tests are proposed in the literature, which is why the tests after Endell (RPW, 2006) and Weißmann (2003) are currently under investigation (figure 3). The tests are based on the mass loss of soil at water immersion. Therefore little cylindrical samples are put into a wire mesh basket which is associated with an electric scale. The water ensures the removing of soil particles which -depending on the wire mesh size and the size of the dropped agglomerates- fall out of the basket. Thereby the basket with the sample loses weight, which is recorded by the scales. The tests after Endell and Weißmann differ in sample size, basket mesh size (there is no definition for the Endell test) and the output data (Endell: decomposition number; Weißmann: decomposition time). Figure 3 gives an idea about the different testing procedures and their disadvantages with respect to the coarseness of the wire mesh basket. In the Weißmann experiment, for example, the small meshes hinder the particles to fall down and in spite of a full decomposition of the sample the effect cannot be recorded.



partly	full	decomposition	partly	full
little	little	soil outside the basket	much	much
low	high	erosion	low	high
low	low	mass loss measured	high	high

Figure 3. Schematic diagram of decomposition tests after Endell and Weißmann

3. GEOTECHNICAL EXPERIMENTS

A variety of mechanisms can lead to dike failure, such as surface erosion due to overflow or wave attack, horizontal sliding, failure on deep slip circles, internal erosion/ piping, and erosion of the dike toe due to lateral flow (Allsop et al. 2006). In the project DredgDikes different mechanisms are investigated, including the slope failure of comparably steep dike slopes, in laboratory and field experiments as well as numerical models. In this paper, a lab test to prepare large-scale surface erosion tests and aspects with respect to the installation technology are presented.

3.1 Laboratory tests and experiments

In addition to the standard geotechnical characterisation, different laboratory experiments have been planned to further define the material behaviour, to account for the difficulties with some standard tests (such as the Proctor test or the determination of the plasticity parameters) and to gain experience for full-scale tests on the test dike. In table 4 the planned tests and experiments are summarised. In the following, first results from a laboratory flume experiment are presented, which have been used to design the full-scale overflowing tests.

Table 4. Overview of laboratory tests and experiments

Topic	Testing facilities	Realised	Started	Planned
Surface erosion	Small-scale laboratory flume experiments		x	
	Decomposition tests		x	
Internal erosion	Piping tests			x
Shrinkage cracking	Climate chamber experiments		x	
	New test setup after Gebissa et al. (2002)			x
	Tensile strength tests			x
Soil mechanics	Triaxial tests		x	
	Proctor tests with varied drying modes		x	
	Microscopic examination of the soil structure		x	
	Organic structure analyses over time		x	
	Comparison of different plasticity tests		x	

For preliminary analyses of the erosion stability of greened and non-greened dredged material a small scale laboratory flume was designed (figure 4). The flume is 2.90 m long and 0.25 m wide and the inclination can be varied up to 1:3. With the associated pumps a flow velocity up to 2.3 m/s and a shear stress of 210 N/m² can be applied. For the experiments greened and non-greened samples of the dredged materials M1, M2 and M3 were prepared. In addition, two non-greened samples of a conventional dike cover material (marsh clay) were used as a reference. The erosion rate of the non-greened samples was estimated by a laser scanner. The results were classified by ASTM-standard D 6460-07 (ASTM, 2006).
Altogether 20 samples (ten vegetated and ten non-vegetated) with a thickness of 7 cm were prepared and compacted in two layers. The degree of compaction ranged from 60 % to 85 %, due to the high initial water content. The lowest compaction was realised on top of an erosion control mat which was covered by 3 cm of dredged material. For the grass cover the same seed-mixture as on the test dike was used (see below).

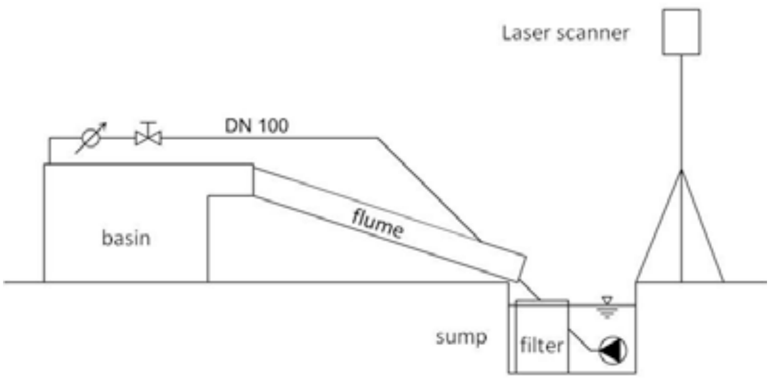


Figure 4. Schematic view of the lab flume experimental setup (Lesch, 2012)

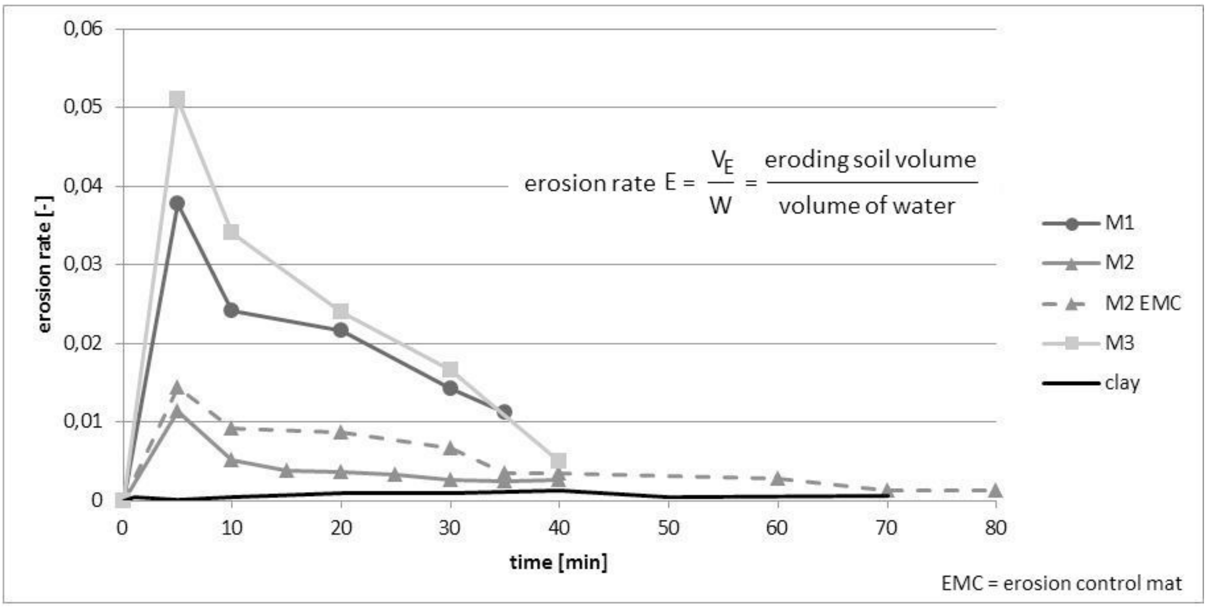


Figure 5. Erosion rates of dredged material and clay

The results of the erosion rate measurements of the non-vegetated samples are shown in figure 5. Among the dredged materials M2 showed the best results, with M1 and M3 showing four to five times the rates. However, all materials possess considerably higher erosion rates than the conventional dike cover material (marsh clay).
The vegetated samples were prepared in the faculty's greenhouses (figure 6A). The root penetration (figure 6B) and density was generally good according to Vavrina (2010). All vegetated samples showed a very high erosion resistance against overflowing. Even a deliberately provoked damage of the sod could not affect erosion apparition (figure 6C). The laboratory flume tests are still on-going, focussing on higher discharge, dried grass cover, and partly vegetated samples.

Figure 6. Sample preparation, root penetration and erosion tests of vegetated dredged materials

3.2 Field Experiments and Installation Technology

A number of field experiments are planned on the test dike and two compaction test fields that had been prepared to test compaction technologies for the test dike and which were also used for turf development tests. Table 5 gives an overview about the planned tests, while in the following the results from the compaction tests with respect to the installation technology are presented.
Two testing fields with a size of 5x10 m each and a height of 1 m have been prepared with dredged materials M1 and M2 to test the compactability with a sheep's foot roller compactor (Figure 8A). The testing fields were built in three layers of 30-40 cm. The differences between the number of crossings and the compactability with and without vibration were investigated. There was no significant increase in compaction ratio with respect to the number of crossings or vibration setups (figure 7). The compaction ratios for material M1 generally vary between 65 and 75 % (water content between 70 and 80 %), for material M2 between 70 and 85 % (water content between 50 and 65 %) (Table 6). In spite of the high water content the workability of both materials can be considered as good. After three days of pore water pressure reduction, the compactability of material M2 was re-determined with values between 80 and 90%.

Table 5. Overview of field experiments

Topic	Testing facilities	Realised	Started	Planned
Surface erosion	Overflowing tests on the German test dike			x
Shrinkage cracking	Fissure analysis on the testing fields		x	
	Fissure analysis on the German test dike			x
Compaction and installation technology	Testing fields - materials M1 and M2	x		
	German test dike - materials M1, M2, M3	x		
Slope stability	Different experiments on the test dike			x
Permeability, infiltration, seepage, piping	Infiltration test on the testing fields		x	
	Infiltration test on the German test dike			x
	Seepage test on the German test dike		x	

Table 6. Comparison between different compaction technologies

Technology	Sheep's foot roller with vibration		Roller compactor with vibration			Caterpillar	
Test site	testing fields		test dike			test dike	
Materials	M1	M2	M1	M2	M3	M1	M2
Water content [%]	70 - 80	50 - 65	46 - 72	42 - 54	31 - 36	62 - 78	46 - 53
Crossings [number]	2 - 8	2 - 8	6 - 8	6 - 8	4	~ 16	~ 16
Realised compaction [%]	65 - 75	70 - 85	72 - 86	79 - 87	88 - 91	70 - 74	78 - 86

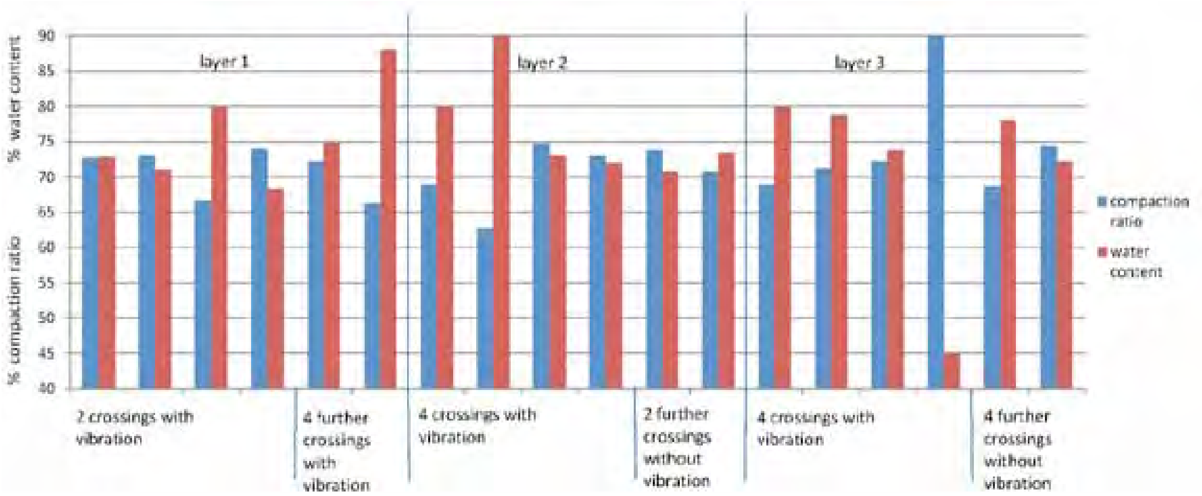


Figure 7. Comparison of water content, crossings and realised compaction on the testing fields for material M1

Figure 8. Three variations of compaction tested on the DredgDikes test dike in Rostock

The test dike was generally built in two steps: The sand core was installed in layers of 0.5 m thickness and compacted to 100% of Proctor density with a roller compactor including vibration (figure 8B). The fine-grained organic dredged materials were compacted in layers of 30-50 cm using a normal roller compactor and in layers of approximately 30 cm only using the caterpillar tracks (figure 8B and C). Compaction ratios of 70% to 91%

were determined, depending on the installation water content, which was generally much higher than the optimal water content derived in the laboratory tests (material drying at 55 °C after German DIN 18127, see above). The results were compared to those obtained from the compaction test field (table 6).
In case of rain, the materials tend to become smudgy, however, rather not because of their PI value but because of their high initial water content near the liquid limit. The ripening in heaps, however, does not allow for much better dewatering. Because of low infiltration on the slopes together with the materials' low permeability the smudgy layer is usually very thin and may rather affect the movability of lorries than that of caterpillars.

4. VEGETATION EXPERIMENTS

The most important aspect for earthen costal protection structures with respect to 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 was tested on all chosen materials, both directly on the storage heaps and on the compaction testing fields. Furthermore, the addition of legumes to a standard dike seeding mixture was tested. Table 7 gives an overview about the different seeding tests.

Table 7: Basic conditions of the different seeding tests

Type of experiment	Seeding pre-test	Compaction testing field	Test dike	Seeding test on test dike embankment
Reference period	4/11 – 10/11	9/11 – 12/12	6/12 – 12/12	9/12 – 12/12
Nb. of test fields	9	2	n/a	27
Materials	M1, M2, M3	M1, M2	M1, M2, M3	M1, M2, M3
State of material	Fine, crumbly	Compacted surface, loosened before seeding	Compacted surface partly loosened. Fine crumbly on erosion control mat	Compacted surface, loosened, application of crumbly topsoil
Seeding mixture	Variations 1/ 2 Self-seeding	Variation 2	Variation 2	Variation 2
Amount of seeds	30 g/m²	30 g/m²	30 g/m²	30 g/m²
Sowing period	spring	autumn	summer	autumn
Additional measures	Irrigation directly after sowing		Irrigation, covering, re-sowing (twice)	Different prepar. modes (figure 13)

4.1 Seed Mixtures

Two different variations of seed mixtures were investigated in the seeding pre-tests (table 8). Variation 1 is a standard seed mixture for dikes. In the variation 2 a portion of legumes was added: White Clover (*Trifolium repens*) and Lucerne (*Medicago sativa*). Additionally, the self-seeding was tested to show the high self-seeding potential of the dredged materials, since they naturally contain a very high percentage of seeds and plant remains which are able to germinate, such as reed (*Phragmites australis*), saltbush (*Atriplex*), sea aster (*Aster tripolium*), quitch (*Agropyron repens*). The composition of the seeding mixtures is presented in table 8. On the compaction testing field and the test dike variation 2 was applied, respectively.

Table 8. Seed mixtures for the test fields and the test dike

composition		portion		seed amount	
cultivar	latin name	variation 1	variation 2	variation 1	variation 2
		[%]		[g/m²]	
Red fescue	*Festuca rubra*	60	54.6	18	16.5
Perennial ryegrass	*Lolium perenne*	30	27.3	9	8.4
Common meadow grass	*Poa pratensis*	10	9.1	3	2.4
White clover	*Trifolium repens*		6		1.8
Lucerne	*Medicago sativa*		3		0.9
Sums		100	100	30	30

4.2 Seeding pre-test

At three chosen dredged material heaps for test dike (M1, M2, M3) the existing vegetation cover was skimmed in April 2011 and a plot of 3x1 m² was prepared respectively (3 variations on 1 m² each, table 7). The plots were framed against lateral ingrowth and watered with 10 l/m² because of considerable aridity before the tests. Immediately, the two seeding mixtures (table 8) were applied by hand, raked in and pressed onto the surface.

The seeding pre-tests confirmed the presumption 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). The soil-borne seeds and plant remains germinated and developed fast in all three variations. In June a first cut was realized. A relatively high cutting protects the freshly germinated grasses and legumes but eliminates most of the bifoliate weeds (*Atriplex* and *Carduus acanthoides*) which are highly competitive but cutting incompatible. The quitch (*Agropyron repens*) with an increased development of runners rather adds well to the seeding mixture. The fine grasses such as common meadow grass and red fescue (*Poa pratensis*, *Festuca rubra*) as well as the legumes (variation 2) were suppressed partly by the heavy growth of the highly competitive ryegrass (*Lollium perenne*). After a second cut the legumes in variation 2 improved their development because of the more favourable light conditions.

4.3 Compaction testing field

After construction of the compaction testing fields in September 2011 the surface of the two materials was roughened about 2 cm deep. The seed was spread evenly, raked in and fixed with a roller (figure 9). 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 (figure 10A). The increased growth of the cultivars was documented by four 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.

Figure 9. Preparation of the compaction testing fields for sowing 2011

Figure 10. Turf development in 2012 at the compaction testing fields

4.4 Test dike

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 (figure 11C), however, on the steeper dike slopes (1:2) a slight slipping of seeds was noticed.

At the test dike the summer sowing proved to be a failure. Neither the hydro-seeding nor the re-seeding with a hand sowing technique (surface roughening, seeding and rolling) resulted in a complete vegetation cover before September. After a first slight growth of grass (figure 12A) an extensive saltbush (*Atriplex*) vegetation cover developed on parts of the test dike (figure 12B). The continuous aridity led to a loss of the germinating seed during the summer, covering only 20 % to 50 % of the area. Blank areas were re-sewn in August. For the reason of dry weather conditions and wind (increasing the surface desiccation) some parts (particularly the overtopping sections of polder 2, see figure 12C) were watered regularly over a period of four weeks. At first brackish water was used due to a lack of fresh water on the test facility, afterwards less salty groundwater was used. However, the irrigation did not improve the germination. In September 2012 one of the overtopping sections was covered with a plastic liner in order to minimize the evaporation. After two weeks considerable germination of the seed was noticed. After removing the liner the development of the seed remained static (figure 12D). Only with significant higher precipitation at the beginning of October and the reduced evaporation the growth of the grasses and legumes improved considerably, especially on the non-irrigated areas.

Figure 11. Preparation and sowing at the test dike

Figure 12. Turf development at the test dike in 2012

M1 0 W WP	**M1 C W WP**	**M1 TS W WP**
M2 0 W WP	**M2 C W WP**	**M2 TS W WP**
M3 0 W WP	**M3 C W WP**	**M3 TS W WP**

M1/ 2/ 3 - *Substrate dredged materials*

Soil preparation:
0 - *compacted surface slightly roughed up, shallow seeding* (1)
C – *Sowing on 5 cm of crumbly dredged material (1,2,3 respectively), raked in and covered* (2)
TS - *Sowing on5 cm of fertile topsoil, raked in and covered* (3)

Further measures:
W - *Irrigation after sowing till growth (< 5 mm/d)* (1)
WP - *wind protection (wooden frame 15 cm high)* (2)
none (3)

Figure 13. Scheme of the seeding test on the test dike embankment with different measures

4.5 Seeding test on test dike embankment

An additional seeding test 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. The scheme in figure 13 shows the different variations in each testing field. On each of the three dredged materials nine test fields were prepared respectively (for example: M1 with soil preparation C -sowing on 5 cm of crumbly M1- and with initial irrigation = M1, C, W).

The tests were installed in mid-September 2012 resulting in a fast and regular greening. The tests did not show a positive effect of the fresh water irrigation, mainly due to some natural rain that occurred approx. one week after seeding. Only marginal differences between the variations could be observed: the vegetation cover in the variations with topsoil germinated quicker and looks a bit more compact.

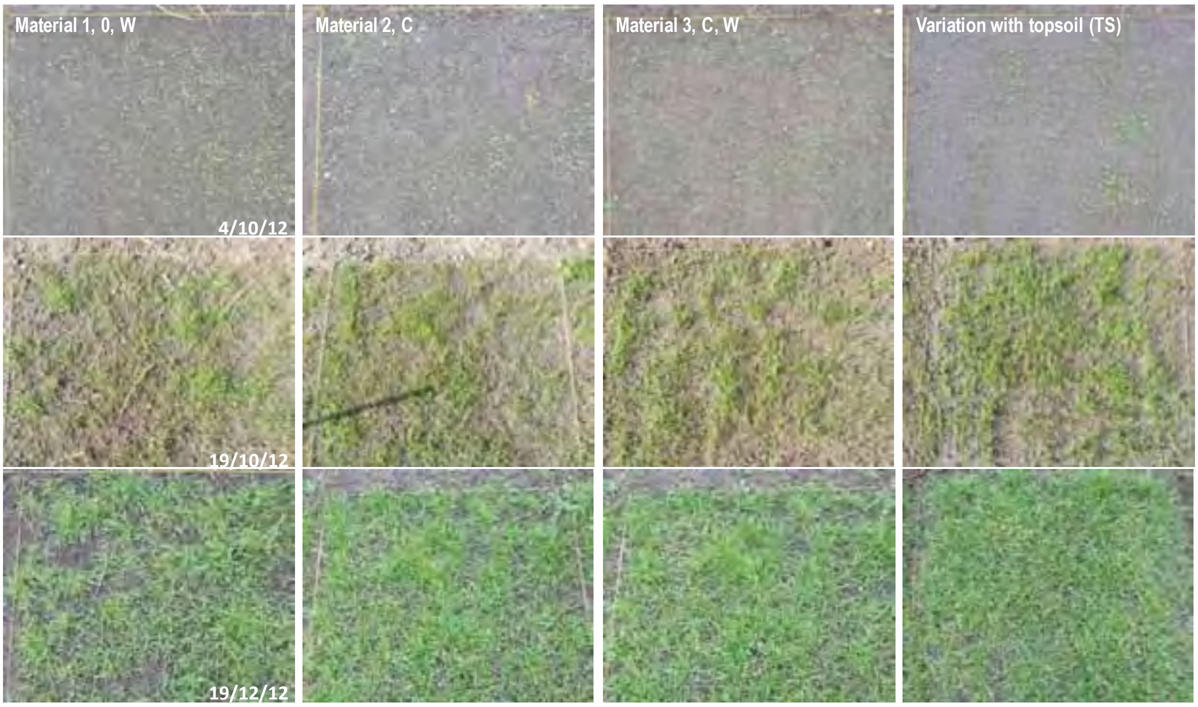


Figure 14. Results of 4 different variations of the seeding test on the dike embankment in the reference period

5. DISCUSSION

The different installation technologies showed that there is no considerable difference in compaction between a seep's foot roller, a normal vibration roller and a heavy caterpillar track, because of the crumbly state of the used ripened materials on the storage heaps. The erosion resistance of the dredged materials as installed in the test dike can be evaluated as good with respect to heavy precipitation and surface runoff. However, the decomposition tests of Weißmann (2003) and Endell (RPW, 2006) as well as the overflowing experiments in the laboratory flume with bare soil samples showed a considerable lower erosion stability compared to a standard dike cover material (marsh clay). Still, the vegetated samples showed a very high erosion resistance, particularly because of the high root density. The samples withstood even higher shear stresses (no destruction at 360 m³/h/m) than those reported from the ComCoast project (maximum 270 m²/h/m; van der Meer et al., 2010).

The determined heavy metal values do not pose a risk for the various subjects of protection, such as soil, groundwater, plants, animals, and humans (compare Henneberg, 1992). Heavy metals and organic contaminants are chemically bonded and not easily available in the fine-grained clayey and organic materials. A change of conditions may occur by reversing conditions (reduction to oxidation); only then possibly contained heavy metals may be remobilised and washed out (Scheffer, 1989). There is an over-supply of nutrients in the materials. Also the salinity is comparably high (a multiple compared to natural low-salt soils). Salt will play no decisive role in coastal regions where the concentrated water flows back into brackish waters. However, it may be of relevance for the ground water if the materials are applied in river dikes in distance from the coast. The risk of dislocation of salt and nutrient ions also exists on the dike surface if there is erosion. Therefore, erosion resistance and protection are even more important than for other dike cover materials.

The chosen seed mixture variation 2 has proven well in practice. Most of the seeds germinate well on all three materials, especially if the substrates are fine-crumbly. Within one vegetation period the seeding mixture cultivates a vital and close vegetation cover. The added cultivars ensure a stronger root formation and entrenchment in deeper soil layers, which is good for the erosion resistance and no problem for the permeability aspects due to the thick dike cover layers of 1.0 and 1.5 m respectively. Both the spring and autumn hand sowing resulted in a successful greening. However, aridity and smooth, compacted surfaces without considerable roughening caused difficulties on the test dike. The hydro-seeding process did not prove for summer sowing at this point. The irrigation with brackish water at the beginning in addition to the existing soil salinity decreased the osmotic potential and reduced the water absorption of the seeds. The repeated desiccation of the seed bed through irregular irrigation together with high daily temperatures caused vegetation loss. High soil temperature conditions caused a delay of germination and a dieback of grass. Moreover, with an increasing temperature the seeds react more sensitive to salinity. The germination process always needs adequate superficial soil moisture which is normally accompanied with sustained humid weather conditions, as well as good soil contact. Soil compaction and sticky siltation/ agglomeration of soil and seed (e.g. through irrigation) hinder germination because of a decreased oxygen content in the surface (Hope and Schulz 1983; Bocksch, 2001; Black and Bewley, 2006). The second re-sowing for test reasons in October 2012 without irrigation showed positive effects for the germination. The general advantages of the autumn sowing are an adequate temperature and prolonged soil moisture (Nonn, 2012). However, sowing in October is usually too late to receive a good turf result for the winter season and should therefore not be recommended. Also, after this long and heavy winter until April 2013, particularly on areas where the snow was blown away, the newly germinated turf has been damaged by frost.

6. CONCLUSIONS

In the project DredgDikes a variety of experiments are on the way to test different dredged materials for their application as dike cover materials. The ripened, fine-grained dredged materials from Rostock can be easily handled, installed and compacted. The erosion resistance seems to be generally good, even if not as good as with standard dike cover materials. If vegetated, however, the fertility and water holding capacity of the dredged materials provide a good establishment of the grass cover and the high root density of the grass-legume mixture provides considerable erosion protection. The chemical analysis mainly results in high salt and nutrient contents, which on the one hand should be kept on the dike slopes by erosion protection measures and which –in case of leachate from the dike body- should not be problematic in a coastal region where the marine dredged material would be applied. With respect to the geotechnical characterisation some problems still have to be solved, particularly concerning the determination of the Atterberg limits and Proctor parameters. In case of organic and lime content the dredged materials should always be characterised with a grain-size distribution determined after their removal to avoid misinterpretation due to agglomerations.
More information -also about the Polish approach on dredged-sand-ash mixtures- can be found on www.dredgdikes.eu.

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