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GEOTECHNICAL CHARACTERIZATION OF DIFFERENT FINE-GRAINED, ORGANIC DREDGED MATERIAL BATCHES FROM THE BALTIC SEA AREA – PECULIARITIES AND ADAPTATIONS

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Abstract. The application of fine-grained, organic dredged material from the Baltic Sea area has been tested for dike construction at the chair of Geotechnics and Coastal Engineering at the University of Rostock since 2007. For this purpose a lot of dredged material batches were analyzed for their geotechnical characterization and erosion stability. For the investigation material with and without conditioning steps (grain-classification, dewatering) was taken off at the spoil fields Drigge (island of Rügen) and Radelsee/Schnatermann (Rostock). The investigated dredged materials can be characterized with high clay, organic and lime content, which affect other geotechnical parameters. The organic and lime content influences e.g. the grain-size distribution because of the agglomeration of organic matter and carbonate with the fine grain. So the mineralogical grain analysis should be carried out after the destruction of organic matter and carbonate. In addition, the organic matter has to be determined in an elemental analyser, because in the standard determination method with a muffle furnace all combustible components are burned and in consequence a higher organic content is examined than it really exists. A further special feature has been showed up at the first performance of the compaction test. Variations of the German DIN standard 18127 in relation to lower drying temperature showed lower compaction densities and higher optimum water contents. So a higher compaction degree could be realized. A clearly defined approach for detecting the compaction density seems to be essential. However, the complete drying and afterwards rewetting for geotechnical characterization of dredged materials material should be avoided. Next to the geotechnical characterization the determination of the erosion resistance is important for dike construction material. The erosion stability was determined by two different disintegration test facilities after Endell and Weißmann. Both disintegration tests showed major limitations to the investigated materials and some boundary conditions have to be discussed critical. The evaluation of the usability of fine-grained dredged material in dike cover layers was investigated after EAK 2002 (2007) and after Weißmann. In two of three evaluation methods, some of the investigated materials could be evaluated as applicable for dike cover layers. Anyway, the high organic content in combination with mostly high water contents has to be evaluated critically.

Keywords: dredged materials, cohesive organic soils, dikes, geotechnical characterization, soil erosion, aggregate stability, disintegration tests

1. Introduction

The maintenance and expansion of waterways and harbours in the North and the Baltic Sea area lead to large amounts of dredged materials every year. Most of the sediments are sandy, non contaminated materials, which can be dumped unproblematically back into the water body. However, the management of fine-grained sediments, which occurs e.g. in harbours or estuaries, is more difficult. Because of the high organic content often associated with contamination (PAH, PCB and TBT) the relocation of fine-grained sediment in the water body is restricted in many regions over the world. Regarding to the OSPAR and HELCOM conventions, cohesive sediments are normally taken ashore. After the dredging and depending on the degree of pollution, the material has to be deposited on special landfills (if they are contaminated) or can be re-used if they are less or non-contaminated.

One promising recycling possibility is the application of dredged material in dike constructions. On the one hand, additional dike construction material is essential for the adaptation of coastal protection structures to the sea-level rise, on the other hand the reclamation of conventional dike construction material like marl and marsh clay has significant interferences with the landscape. A substitution with dredged sediments saves resources and reduces generated waste.

In the past some successful pilot projects with sandy and cohesive dredged material from the rivers Elbe and Weser (German North Sea area) were initiated. The main emphasis was put on the geotechnical ability for dikes (Gebert et al. 2010, Zöller 2005) and on the cracking analysis and erosion resistance of conditioned dredged material (Bayer et al., 2012). The results were integrated into the *Recommendations for the design of coastal protection constructions* (EAK 2002, 2007), where parameters for the characterization of dredged materials has been evaluated. Further investigations with dredged materials in dike constructions have been performed in Bremen (Umtec feasibility study, 2008), but applications beyond pilot projects could not be realized until now.

Next to the investigations on the North Sea the chair of Geotechnics and Coastal Engineering at the University of Rostock has been examining the application of fine-grained, organic dredged material from the Baltic Sea area for dike construction since 2007 (Saathoff et al., 2014). The materials of the Baltic Sea area differ to that of the North Sea; mainly there is less fine-grained material with less contamination. Therefore the material treatment before re-use can be limited to grain-size classification and dewatering. Here, two possibilities of dredged material management technologies can take place: (1) The material is pumped into containment areas for primary dewatering. When the material has sufficient strength for removal the mud is taken out and put on heaps on special drying areas for further dewatering. After the ripening progress the material is usually an inhomogenous mix of mineral and organic soil particles. One example is the containment area Drigge on the island of Rügen. (2) A classification in "longitudinal stream classification polders" is used, where the soil particles drop down depending on their particle size: the sandy material settles down around the inlet, followed by a silty mixed soil in the middle of the polder. At the end of the polder the finer clayey and organic particles settle as an organic sludge. With this method different material batches with different grain composition occur, which can be removed and processed separately for a qualitative better and more homogenous material. The Hanseatic City of Rostock runs two such containment areas, "Radelsee" and "Schnatermann". In summary two different dredged material conditions are available for the re-use in dike constructions: a) a separated (fine or coarse grained), homogenous material and b) an inhomogenous mix of mineral and organic particles (Fig. 1).

Fig. 1. Dredged material management in Rostock and Drigge

At the University of Rostock two projects deal with the re-use of conditioned and non-conditioned dredged materials from the Baltic Sea area in dike constructions. In both projects questions about the best characterization methodology for cohesive organic soils from the Baltic Sea area as well as the stability under static loading are subject of the investigations. The results of the characterization are essential for the evaluation of the applicability of dredged materials in dike constructions and will be presented in this paper. Next to the comparison of different characterizing methods, the peculiarities and possible adaptations for the geotechnical characterization of cohesive organic soils are proposed and discussed critically.

2. Materials

For the geotechnical characterization five different cohesive dredged material batches were analyzed: four different conditioned and ripened materials from the containment facility of the Hanseatic City of Rostock (materials M1, M2, M3 and S2) and one non-conditioned dredged material from the containment area Drigge (material D). An Overview about the regional provenance can be taken from Fig. 2.

The materials differ in the geographic origin (Baltic Sea area for material D, river and estuary sediments for materials M1, M2, M3 and S2), different (Rostock) or no (Drigge) conditioning steps, the composition (fine-grained, organic sediments and sandy silty materials) and the ripening time: the materials M1 and M3 had been ripened for five years, while the materials M2 and S2 had been ripened for two years at the time of the initial investigations. Material D was left in the containment area with no further treatment or dewatering until the extraction for the pilot dike. For each material, a range of one to four subsamples (depending on the amount of the material) were taken at a depth of 0.3 till 0.5 m. For the Rostock-materials, mixed samples from different areas of one or more single heaps were taken, whereas in Drigge the subsamples were removed directly from the test dike after its installation. An impression of the different investigated dredged materials can be taken from Fig. 3. The analysis of the erosion

Fig. 2. Overview about the regional provenance

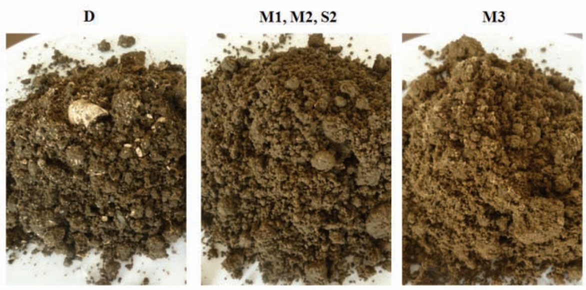

Fig. 3. Investigated dredged materials

stability under static loading was performed with the materials M1, M2 and M3. Further investigation with materials S2 and D are currently on the way.

3. Investigations

The materials were investigated according to the German DIN standards for soil mechanical analysis (DIN, 1998). This includes mechanical characteristics like grain-size distribution, compaction parameters, plasticity, shear strength and water permeability. In addition further investigations according to the grain-size and organic determination were performed, which consider the special characteristic of the investigated dredged materials with high organic and lime content. This involves the grain-size distribution after DIN ISO 11277 with the removal of organic matter and carbonates using hydrogen peroxide and hydrochloric acid (Fig. 4) and the TOC determination (total organic carbon) after DIN ISO 10694, which is analyzed with an elemental analyzer at temperatures above 1,000°C.

Further analyses were performed in the proctor compaction test regarding the drying temperature and drying mode. Background is the specification of the German DIN standard, in which a drying process below 60°C for fine-grained and organic soils is demanded. Moreover, the soil hast to be dried until a water content between the plastic and the shrinkage limit. Because of initial problems in determining the plastic and shrinkage limit compared with difficulties in the execution of the proctor test (materials were mostly too wet after the drying until shrinkage limit), investigations with various drying temperatures (oven and air drying) and drying modes (complete or partial air drying) were examined. The aim of the investigations was the detecting of a general execution of the proctor compaction test for fine-grained organic dredged material.

For determining the erosion stability under static loading the disintegration tests after Endell (enhanced by the Federal Waterways Engineering and Research Institute, BAW) and Weißmann were performed. Both tests have a similar test setup, where cylindrical, Proctor compacted samples with different water contents are put into a wire mesh basket which is then immerged into a water basin. For measuring the sample weight during the investigation the wire mesh basket is connected to an electric scale. The investigation starts when the soil sample is placed into the water basin. Through the water influx the sample begins to crumble and soil particles fall off the wire mesh basket (Fig. 5). This leads to a sample weight reduction which is recorded as a function of time. Both disintegration tests

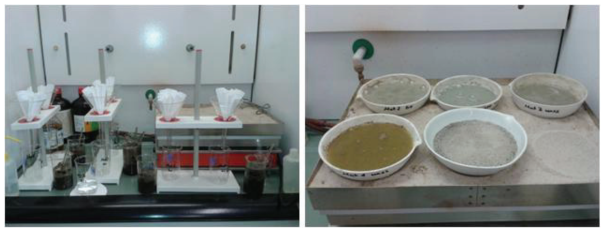

Fig. 4. Removing of organic matter and carbonate with a) HCL and b) H_2O_2

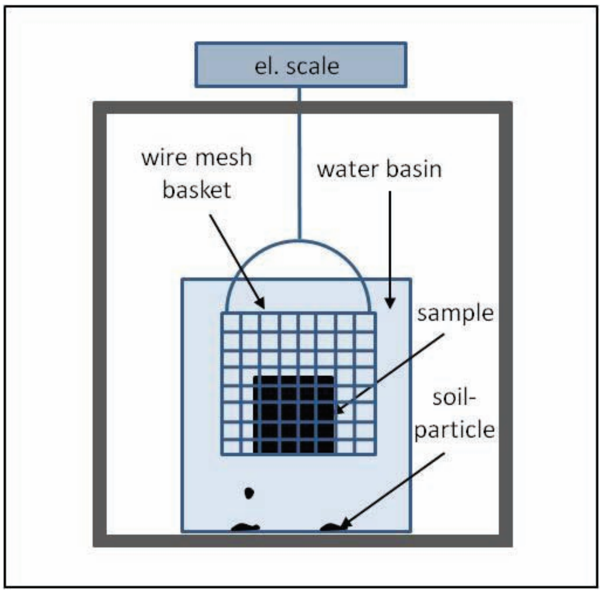

Fig. 5. Disintegration tests, schematic (Große et al., 2014)

Table 1. Boundary conditions for disintegration tests

	Endell	Weißmann
Water type	Distilled water	Tap water
Sample size	H = 4 cm, D = 2 cm	H = D = 5 cm
Basket	Not defined; chosen: cylindrical shape with H = 5 cm, D = 3.2 cm	Cubical form with A = B = 10 cm and H = 12 cm
Sample conditions and number of samples	≥ five samples at various w; Each one subsample	Three conditions after compaction: 1) oven-dried 2) w_{opt} (here: w_n) 3) wet sample; Each three subsamples
Compaction condition	various w through drying and wetting	w_{opt}; here modified with w_n
Result	Disintegration number Z(t)	Disintegration time $t_{30,w(v)}$

differ in sample size, testing procedure and water type. A short overview about the boundary conditions is presented in Table 1.

A further difference exists in the results evaluation. For the disintegration test after Endell (BAW) the disintegration number Z(t) as a function of time is calculated for every subsample with the following equation 1.

$$Z(t) = \frac{A1 - A(t)}{A1 - A2} \quad (1)$$

Z(t) Disintegration number as function of time
A1 Uplift sample weight including mesh basket weight [g] at the beginning
A(t) Uplift sample weight including mesh basket weight [g] at the time t of the test
A2 Uplift mesh basket weight [g] without sample

Endell mentioned that for every soil one specific water content constitutes the lowest disintegration number. This can be mostly expected at a water content near the liquid limit, so a range of at least five different water contents have to be investigated. In addition the investigation can be considered only if all particles, which dropped off the samples, have passed the wire mesh basket. Should this not happen, the investigation has to be repeated. For the comparison of different soils the disintegration number after eight hours Z(8) is used. After the RPW (2006) a disintegration number Z(8) ≤ 0.05 [-] is proposed for evaluating mineral clay liners as erosion resistant.

In the Weißmann test the disintegration time $t_{30,w}$ is examined, which is described as the time when a sample has lost 30 % of its initial weight. The test has to be finished if the weight loss of 30 % is recorded, but at the latest after 24 hours. After the compaction at optimum water content the investigations are performed with three different water conditions: I) oven dried sample, where the previous compacted sample is dried in an oven at 50°C, II) sample at opt. water content with no further preparation and III) water-immerged samples, where a sample is lagged with filter paper and put into a water basin for ten minutes, afterwards it is kept into a desiccators for 24 hours. For each of these condition three subsamples are examined, each with a separate disintegration time $t_{30,w}$. The results must be entered into a diagram with $t_{30,w}$ = f(w), which describes an exponential curve (Weißmann, 2003). With the help of the results and two further, free elected water contents, which are contained from the diagram $t_{30,w}$ = f(w), the auxiliary parameters A and B can be calculated (equations 3 and 4). Thereafter the reference disintegration time $t_{30,w(v)}$ is evaluated at a Consistency Index of Ic = 0.8 [-] (equations 2 and 5). Because of several problems with dredged material in initial tests the preparation methodology was modified. Instead of the compaction at optimum water content the natural water content was chosen. This belongs to problems in determining the optimum water content and a spread in disintegration curves coupled with less disintegration numbers or soils compacted at optimum water content.

$$t_{30}(w) = t_{30,0} + A * w * e^{B*w} \quad (2)$$

$$B = \frac{\ln((t_{30,0(w1)} - t_{30,0}) * w2) - \ln((t_{30,0(w2)} - t_{30,0}) * w1)}{w_1 - w_2} \quad (3)$$

$$A = \frac{t_{30,0(w1)} - t_{30,0}}{w_1 * e^{B*w1}} \quad (4)$$

$$w_V = 0.2 * w_L + 0.8 * w_P \quad (5)$$

$t_{30,0}$ Disintegration time t_{30} at w = 0
A,B Auxiliary parameter
w_v water content at Ic = 0.8

4. Results

4.1 Geotechnical characterization

The results of the geotechnical characterization, which was examined in accordance with the German DIN-standards for soil mechanical analysis, are presented in Table 2.

All materials can be characterized as fine-grained, organic and limy soil with high water contents, even after a long ripening time. A conspicuous aspect is the missing clay content in almost every dredged material by determining the grain-size distribution after DIN-standard 18123. The only exception is material D with a clay content of 10 to 13 %. The sand content varies from 26 to 43 % for the materials M1, M2, S2 and D and 52 % for material M3, which is therefore the sandiest material. Despite of the high water content the initial shear strength c_u, which was determined with the laboratory vane tester, is relative high for all materials from the containment area Rostock, while the material D from the containment area in Drigge shows lower shear strengths at similar grain size distributions and similar water contents. Moreover, the same result is determined at materials M1 and M2 which differ mainly in the time of the ripening process. In addition, there is a big difference between the natural and the optimum water content (w_n and w_{opt}) in all materials. All dredged materials show less water permeability k_f and can be classified as “very weak impermeable” after DIN-standard 18130. The investigation was done with a load of 0.3 bar (which represents the maximum height of the test dike) and a successive saturation (so called “B-test”), which ensures that the sample is not pressed through high pressure and get therefore lower permeability. The angle of friction φ and the cohesion c were determined with the direct shear box (sample size Ø 7.1 cm) with loads of 50, 100 and 200 kN/m² and show both high results. The plasticity varies from very high liquid and plastic limits (LL and PL) for material M1, M2, S2 and D to lower Plasticity for material M3, which is mainly caused in the grain-size distribution.

Table 2. Results according to German DIN-standards for soil mechanical analysis

Material	M1	M2	M3	S2	D
Clay [%]	0	0	0	0	10 - 13
Silt [%]	59 - 67	60 - 62	46	55	46 - 62
Sand [%]	33 - 41	36 - 39	52	43	26 - 42
w [%]	61 - 68	55 - 73	46	44 - 50	62 - 76
LL [%]	111	96	63	90	74 - 102
PL [%]	75	60	45	62	24 - 34
SL [%]	43 - 45	39 – 40	32 - 34	45-46	32 - 43
Vs [%]	41 - 42	40	23 - 27	40	18 - 54
PI [%]	36	36	18	28	50 - 68
CI [-]	1.1	0.7	0.9	1.4	0.3 - 0.7
OM [%]	13 - 14	12 - 14	9	11	9 - 12
LC [%]	9 - 10	8	10	1 - 2	4 - 7
c_u [kPa]	53 - 132	19 - 34	120	51 - 67	7 - 20
φ [°]	28 - 30	28 - 31	30	31	20 - 29
c [kPa]	35 - 47	13 - 19	59	51	7 - 15
DD [g/cm³]	0.85 - 0.9	0.87 - 0.97	1.09	0.99	0.84 - 0.94
k_f [m/s]	4 - 6E-8	7 - 9E-10	2E-9 - E-8	6E-9	4E-10 - 7E-9
w_{opt} [%]	40 - 43	32 - 35	31	40 - 43	24 - 32
OD [g/cm³]	1.2	1.3	1.4	1.1	1.3 - 1.4

For material M1, M2, S2 and partly for material D a high degree of shrinkage Vs can be recognized as well. The results of the additional examined investigations for grain-size distribution (after DIN ISO 11277) and TOC content (after DIN ISO 10694) are shown in Table 3. Within these results a significant higher clay content compared with a lower silt content can be recognized. In addition the organic matter OM, calculated on the TOC value with a factor of 1.724, shows considerable lower results.

Table 3. Results of TOC and grain-size analysis with removing of organic matter and carbonate

Material	M1	M2	M3	S2	D
Clay [%]	25-28	22-25	15	21	15-19
Silt [%]	41-44	32-38	31	42	33-41
Sand [%]	29-34	40-47	54	37	43-51
TOC [%]	6-7	5-6	3	6	3
OM [%]	10-11	9-10	6	10	5-6

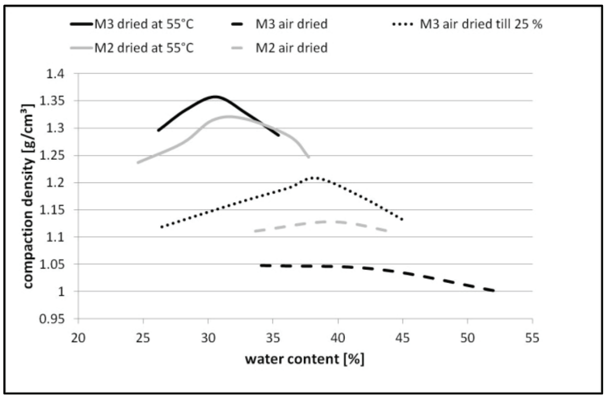

Fig. 6. Variation of the proctor compaction test

The results of the proctor compaction tests are presented in Fig. 6 and show considerable differences between the single drying methods. In general a lower proctor density OD coupled with higher optimum water content w_{opt} could be observed with the complete air drying instead of the oven-drying, but not such a high optimum water content w_{opt} and low proctor density OD at the partial air drying until a water content of w = 25 %.

4.2 Disintegration tests

Both disintegration tests were performed with materials M1, M2 and M3. For the Endell test five subsamples with different water content were investigated for materials M1 and M2, whereas for material M3 seven subsamples were examined. However, the Weißmann test was performed with two different samples for material M1 and M2 and only one for material M3. Investigations to material S2 and D are currently on the way and will be presented at a later time.

4.2.1 Disintegration test after Endell (BAW)

For material M1 and M2 the results of the disintegration tests after Endell (BAW) are exemplary shown on material M1 (Fig. 7), because the curve shapes of both materials are very similar. In the diagram all five subsamples from one material, each with a different water content, are presented in one chart for better comparison.

All samples, independent on their water content, start to crumble already after a short period of time and show, moreover, a considerable weight loss until a time-interval of about 1,000s. At that time most of the samples have already lost 50 till 70 % of their primary weight. In the remaining period until the end of the investigation almost all sample have a relative constant residual weight. One peculiarity from this curve shape shows all samples with lower water contents: After they are put into the water basin a short weight increase can be recognized, which repeats at the end of the investigation.

In Fig. 8 the disintegration behaviour of material M3 is presented, which is considerable different from that of material M1 and M2: The more sandy material M3 shows a total or almost complete decomposition of most of the samples already within a time period of 100s. Two exceptions of this phenomenon can be recognized with the sample at natural water content (w_n = 49.7 %) and the sample at w = 36.9 %. Further it is conspicuous that samples with nearly the same water content show considerable different disintegration behaviour, e.g. the sample with the natural water content w_n = 49.7 % to that of the sample with w = 49.1 % or both samples with a water content of w = 36.0 % and w = 36.9 %. The evaluation of the disintegration numbers after eight hours Z(8) show mostly the lowest disintegration time for samples at natural water content (w_n). The results are presented in Table 4**.**

4.2.2 Disintegration test after Weißmann

Due to the Endell test, the investigations of the Weißmann test show very similar results for each dredged material, wherefore the disintegration curves of only one material are presented exemplary in Fig. 9. For overview purposes only one subsample is shown for each of the three conditions, because a large accordance of the three subsamples occurs.

For every condition a different curve shape has been recorded. The oven-dried samples show an enormous weight increase with partly 260 % of the initial sample weight, although dropping soil particles can be recognized during the whole investigation. In addition, large air bubbles escape from the sample especially in the first testing period. Until the end no weight loss and, therefore, no disintegration time t_{30} can be calculated.

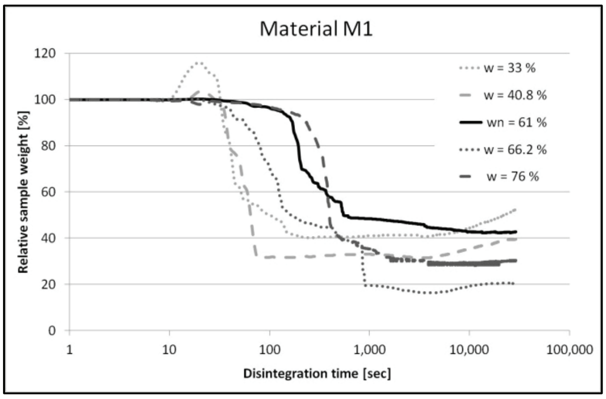

Fig. 7. Disintegration curves (Endell) of material M1 (Große et al., 2014)

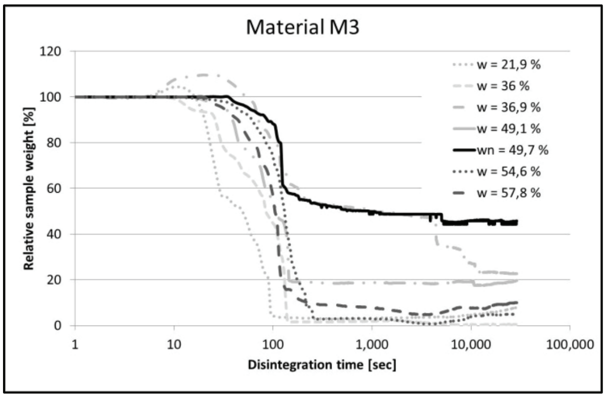

Fig. 8. Disintegration curves (Endell) of material M3 (Große et al., 2014)

Table 4. Results of the disintegration test after Endell (BAW)

Material	w [%]	Z(8)
M1	33.0	0.7273
	40.8	0.6056
	w_n = 61.0	**0.5728**
	66.2	0.6954
	76.0	0.6056
M2	30.0	0.7273
	42.0	**0.3991**
	w_n = 54.0	0.4714
	78.0	0.4784
	79.0	0.6348
M3	21.9	0.9206
	36.0	0.9958
	36.9	0.7273
	49.1	0.8033
	w_n = 49.7	**0.5425**
	54.6	0.9524
	57.8	0.9003

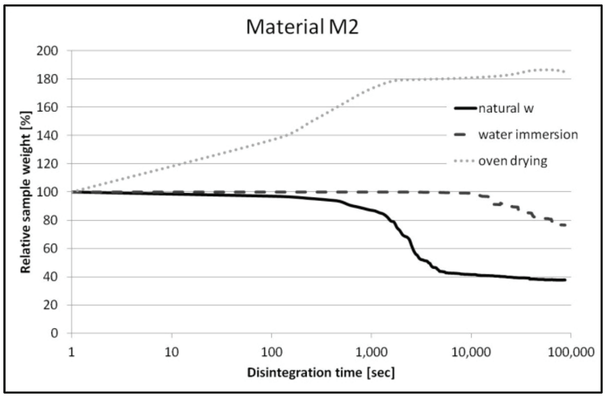

Fig. 9. Disintegration curves (Weißmann) of material M2 (Große et al., 2014)

Table 5. Disintegration times $t_{30,wn}$ for M1, M2 and M3

Material	No.	$t_{30,wn}$ [s] for subsample			Ø $t_{30,wn}$ [s]
		1	2	3	
M1	2	1,440	1,560	1,800	1,600
		1,080	1,320	1,600	1,320
M2	2	2,040	2,760	3,000	2,600
		2,880	3,600	5,520	4,000
M3	1	960	1080	1,320	1,120

The water-immersed samples show no sample weight reduction within the first part of the investigation, although again dropping aggregates can be observed. The first weight loss can be recorded after a time-period of about 10,000s, which happened in a slowly way. At the end of the investigations all subsamples show a weight reduction of about 20 % of its initial weight, with which again no disintegration time t_{30} can be evaluated. For samples examined at the natural water content the highest disintegration of all conditions could be observed. The weight loss starts approximately after 100s and ends with a sample weight reduction of 60 % at a time of about 10,000s.

The disintegration time t30 is calculated at that time when a sample has lost 30 % of its initial weight, which is not achieved by the oven and the water immersed samples. On this account these samples get a disintegration time $t_{30,w}$ of 86,400s. The results of the samples at natural water content are presented in Table 5. For materials M1 and M2 two investigations with each three subsamples were examined, whereas for material M3 only one investigation was performed. For each investigation an average disintegration time Ø $t_{30,wn}$ was calculated.

Because of the lower disintegration time of samples at natural water content in comparison to the oven-dried and the wetted samples, no dependency of disintegration time and water content could be described. In the consequence no disintegration time $t_{30,w(v)}$ was calculated for the investigated materials.

5. Discussion

5.1 Geotechnical characterization

The specialty of the investigated dredged materials can be described by relatively high clay content in connection with a high content on organic matter and lime. All three parameters influence the characters of the material as well as their characterization in a particularly way.

One special effect occurs to the grain-size distribution, where the organic as well as the lime fraction forms agglomerates with the fine particles (Blume et al, 2010). These relative heavy agglomerates sink much faster than the pure clay particles and are therefore detected as coarse particles. This effect can also be seen visually with a clear separation between the soil suspension at the bottom and the water above. In the consequence, a low or partly missed proportion of fine-grained particles are detected, which could be observed in the investigations after DIN-standard 18123. One solution to this problem proposes the German DIN-standard 11277 with the grain-size determination after destroying of organic matter and carbonate with hydrogen peroxide and hydrochloric acid. With this method a considerable higher clay content of dredged material could be detected (Fig. 10).

Consequently the classification of the dredged materials after the soil type triangle changed, e.g. for material M1 and M2 from “loam” to “silt loam”. But at the present, the knowledge on the removal of soil organic matter and the effects of the oxidants on the soil minerals is incomplete (Mikutta et al., 2005). Further, a major influence exists on the clay minerals by the heating relating to the organic matter removal. On this account a performance of both determination methods (with and without removing of organic matter and carbonate) would be preferred. A further special characteristic occurs during the determination of the organic content. For the analysis a muffle furnace is usually used (DIN-standard 18128), where the previous dried and fine crushed soil is burned at a temperature of 550°C and the mass loss through the burn of organic compounds is detected. Because of the marine origin a high lime content can be recorded in all dredged materials which are burned equally during the combustion process.

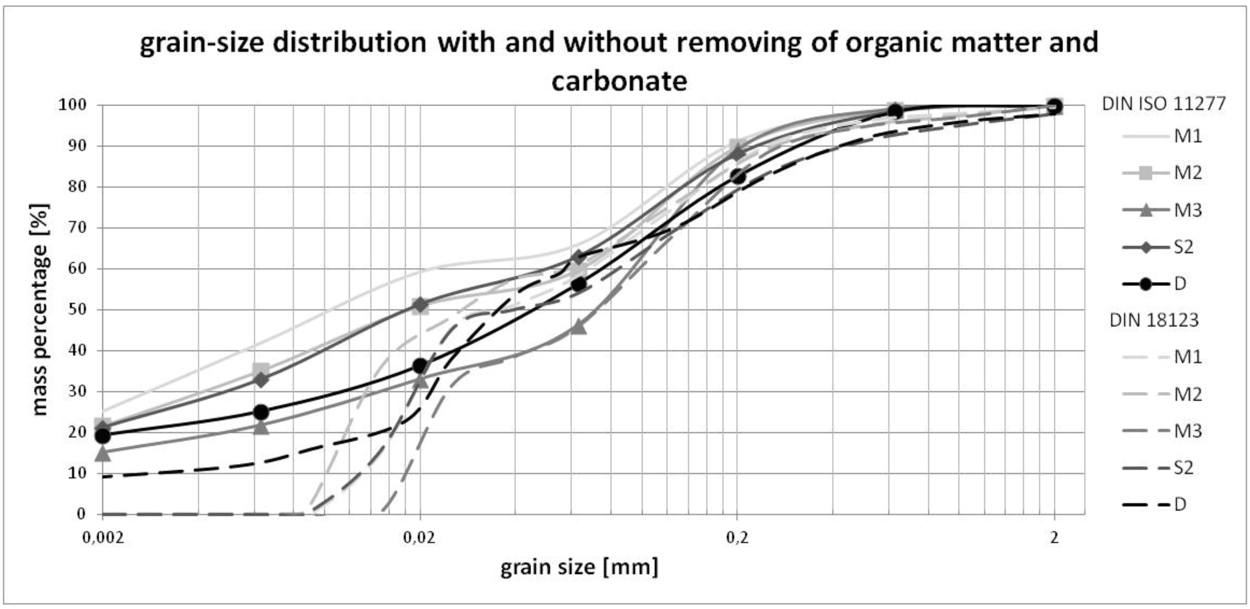

Fig. 10. Grain-size distribution with and without removing of organic matter and carbonate

Table 6. Organic matter (OM) after DIN 18128 (*) and DIN 10694 (#)

Material	M1	M2	M3	S2	D
OM* [%]	13-14	12-14	9	11	9-12
OM# [%]	10-11	9-10	6	10	5-6

Table 7. Plasticity parameters with (*) and without (#) removing grains > 0.4 mm

Material	M1	M2	M3	S2	D
LL [%]*	111	96	63	90	74-102
PL [%]*	75	60	45	62	24-34
SL [%]*	43-45	39-40	32-34	46	32-43
PI [%]*	36	36	18	28	50-68
CI [-]*	1.1	0.7	0.9	1.4	0.3 – 0.7
LL [%]#	80-98	64-88	52-57	73-74	-
PL [%]#	75-81	54-67	49-54	67-69	-
SL [%]#	58	42-47	51	54-64	-
PI [%]#	4-22	11-24	3-4	4-7	-
CI [-]#	2-5	0.5-0.9	2-4	3-7	-

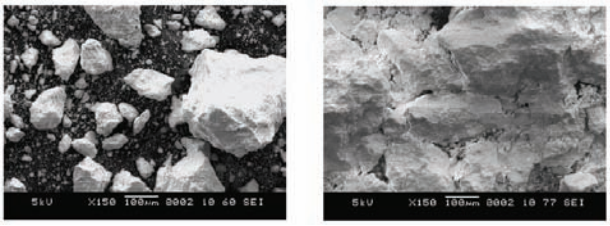

Fig. 11. Agglomeration of a) air-dried sample and b) oven dried sample (Sunil and Krishnappa, 2012)

Consequently, a higher mass loss and, therefore, a higher organic content is determined than actually exist in the material (Table 6).

The results of the proctor compaction test show a considerable influence of the drying temperature to the proctor density and the optimum water content. One explanation for this phenomenon could be the agglomeration of fine particles among each other and with organic compounds at higher drying temperatures. The agglomeration leads to larger grain-sizes coupled with a lower specific surface (Mikutta et al., 2005), which produces lower optimum water contents as result of lower water absorbency. At the same time the proctor density increases as result of the larger grain sizes. Similar results have been observed by Sunil and Krishnappa (2012), who examined the influence of drying temperatures on index properties of lateral soils. Within the investigation, X-ray tests show a considerable agglomeration for soils which was dried at higher temperatures in comparison to soils dried at lower temperatures (Fig. 11). Hesse (1971) mentioned further an existing irreversible dehydration process caused by drying, which leads consequently to a cementation of clay particles. According to this statement the observed lower water content and higher proctor density by drying until a water content of 25 % is remarkable because the partial drying should rather minimize the agglomeration and cementation process in the material. An explanation to this phenomenon could not be given at the moment, but further tests to the influence of the drying temperature are on the way.

The plasticity parameters were examined according to the German DIN-standard 18122, which represents the Atterberg method for determining the plastic and liquid limit. In this regulation a pre-treatment with the removal of grains larger than 0.4 mm is prescribed, which have been done in the investigation. Through the elimination of the sandy particles, the material cannot be characterized as the origin material and show further a considerably different plasticity behaviour than investigations with the whole material (Table 7).

In consequence the renunciation of the pre-treatment should be preferred, but some problems in determining the plastic limit with the roll-out test occur. Within these investigations the material starts to flake before the 3 mm diameter was reached, and no resilient plastic limit could be examined. In addition, both the plastic and the liquid limit are dependently on the experience and expertise of the operator (Andrade et al., 2011). According to this statement some researches prefer the “direct methodology” for determining the plasticity. Instead of the indirect method, where a moisture content at a defined consistency is measured (Baran et al., 2001), the “direct methods” determine the effect of the moisture content and “other variables” on the relationship between an applied force and the resulting deformation (Florales et al., 2010). Examples for indirect methods are the Atterberg and the Pfefferkorn method, whereas compression tests can be used for the direct method. The most advantage of the direct methods is the use of materials without any pre-treating. On this account investigations to measure the plasticity with the compression test are currently on the way.

5.2 Disintegration tests

In both disintegration tests a lot of major problems due to the testing procedure as well as to the experimental setups occur. The main concept of disintegration tests is the crumbling of the sample through water injection, which leads to dropping soil particles from the sample. When the dropped particles fall out of the basket, a reduction of the sample weight can be recorded.

In a great number of investigations the main problem was the fact that a lot of the dropped particles stayed inside the basket (Fig. 12) and did not fall throughout the meshes. In consequence, no weight loss could be recorded. One reason for this is the small mesh sizes, where larger agglomerates could not pass the basket. Endell (RPW, 2006) mentioned a repetition of the investigation in this case, but this is no good approach because some materials decompose always in larger agglomerates. One solution could be the use of baskets with larger mesh sizes, but especially for the small samples of the Endell test the danger of a falling

Fig. 12. Dropped agglomerates stay inside the basket

Table 8. Results of disintegration tests at w_n-samples

Material	Z(8), w_n [-]	Ø $t_{30,wn}$ [s]
M1	0.5728	1,320 and 1,600
M2	0.4714	2,600 and 4,000
M3	0.5425	1,120

over or a falling throughout the meshes exists. An adaptation to larger mesh sizes could be only done in accordance with a larger sample size.

After Endell (BAW) a mineral clay liner can be evaluated as erosion resistant if the disintegration number Z(8) is below 0.05 (RPW, 2006), but neither one of the three investigated dredged materials achieved this value rudimentary. One explanation could be for sure the lower clay content compared to mineral clay liners, but many further reasons are possible: For most of the materials the samples at natural water content show the lowest disintegration number Z(8), that is why the sample preparation seems to play an important role. Especially the drying of samples with a water content below the natural water content seems to have a substantial influence of the aggregate stability, which results again through the agglomeration of fine particles among themselves and with organic (Basma et al., 1994; Sunil and Krishnappa, 2012). Due to the dehydration and the cementing effect (Hesse, 1971), the larger grain-size reduces the cementing ability of the materials and the samples start their crumbling process earlier and in a larger scale. Besides the drying, the preparation with water addition has an influence of the sample stability as well. At the beginning a lower crumbling process can be observed for the water added samples, because in comparison to the natural or the dried samples the micro pores are more saturated with water. This leads to a lower water injection into the sample. After some time the behaviour changes and the wet samples show a considerable higher crumbling than samples with natural water content. An explanation could be the decreasing aggregate cohesion with increasing investigation time as result of the previous water addition. So finally, Endell's statement with a lower disintegration time at the liquid limit cannot be validated.

The evaluation of the Weißmann tests bases on the calculation of the disintegration time $t_{30,w(v)}$, for which a dependency of increasing disintegration time at increasing water content is necessary. This dependency could not be observed during the investigations with fine-grained dredged material. The oven-dried samples showed an extensive weight increase instead of a mass loss, which is caused in the enormous water absorption through the high suction of dried samples. The fast infiltration leads further to a quick dislocation of included air (Rohoskova and Valla, 2004), wherefore large air bubbles come out of the sample coupled with dropping aggregates. This process is a consequence of the overpressure in the sample and is called "aggregate blasting" (Auerswald, 1993; Le Bissonais, 1996). Because of the non-existent dependency of disintegration time and water content, the evaluation of the erosion resistance after Weißmann was examined and compared to that after Endell (BAW) at natural water content (Table 8).

In both disintegration tests the best erosion resistance was obtained at material M2 with a disintegration number of $Z(8)_{,wn}$ = 0.4714 and a disintegration time $t_{30,wn}$ = 2,600s and 4,000s. The ranking of material M2 and M3 vary in both tests: In the Weißmann test material M2 showed a lower disintegration time than material M3, whereas in the Endell tests the behaviour changed and material M3 showed better results. The result of the Weißmann test is more believable because material M3 posses a higher sand content which should lead to higher disintegration.

However, the evaluation of erosion resistance on the natural water content is restricted in the case that the natural water content represents only one temporary condition of the dredged material. The use of "constant conditions" which are comparable for different materials (e.g. liquid or plastic limit) would be convincing. The problem here is again the necessary preparation with drying or wetting of samples, which leads to higher disintegration. For the preparation a solution has to be found. In conclusion the application of disintegration tests as yet is not advisable for cohesive dredged materials. Further adaptation is needed which come up with the specialty of the material.

5.3 Applicability for dike constructions

The applicability of fine-grained dredged material for dike cover layers can be validated with different evaluation methods. One possibility for dredged material is described in the EAK 2002 (2007). There the limited values can be chosen after "glacial loam / marl" and "harbour sludge". In this investigation the limit values for "harbour sludge" were elected, because the geotechnical properties of glacial marl show considerable differences to that of the investigated materials. The parameters with the associated limit values as well as the results of the dredged material evaluation are presented in Table 9.

Table 9. Evaluation after EAK 2002 (2007) for "harbour sludge"

parameter	Limit value	M1	M2	M3	S2	D
OM [%]	≤ 20	13-14	12-14	9	11	9-12
Clay [%]	≥ 15	25-28	22-25	15	21	15-19
Sand [%]	≤ 40	29-34	40-47(*)	54*	37	43-51*
Cu [kPa]	≥ 15	53-132	19-34	120	51-67	7-20(*)

Table 10. Limit values for marsh clay after EAK 2002 (2007)

Parameters	Limit values		
	Well suited	Suited	Limited suited
Soil type	Silty/clayey marsh clay	Sandy marsh clay	Heavy sandy marsh clay
Clay [%]	20-40	15-20	10-15
Sand [%]	10-40	25-50	30-50
LL [%]	35-70	30-55	25-40
PI [%]	20-45	15-20	10-15
W [%]	25-60	25-50	25-45
DD [g/cm³]	1.1-1.45	1.15-1.5	1.25-1.55
c_u [kPa]	≥ 25	≥ 30	≥ 40
OM [%]	≤ 10	≤ 10	≤ 5

Table 11. Dredged materials evaluated after marsh clay (EAK 2002, 2007)

Material	M1	M2	M3	S2	D
Clay [%]	3	3	2	3	2
Sand [%]	3	1	0	2	1
LL [%]	2	2	1	2	2
PI [%]	3	3	2	3	3
W [%]	0	0	3	3	0
DD [%]	0	0	0	0	0
c_u [kPa]	2	2	2	3	1
OM [%]	0	0	3	0	1
∑ EN	13	11	13	16	10

According to "harbour sludge", the materials M1 and S2 observe all limit values and can be therefore advised as dike cover layer. Because of a partial restriction to the sand content, material M2 can be described as limited applicable. Contrary, material M3 has a considerable too high sand content for dike cover-layers, but could be used e.g. for homogeneous dike sections. The worst rating gets material D, because next to the high sand content especially the initial shear strength is partly too low for dike constructions. One reason for this result could be the limited dredged material management at the containment facility Drigge, where no further treatment happened after the dredging into the polder. In contrast, the dredged materials in the containment facility in Rostock were mixed several times due to transformation processes and were dewatered afterwards on separate ripening polders. This could lead consequently to higher shear strength at similar material composition by e.g. better structure formation or different degradation processes of the organic. However, it is questionable if the classification after "harbour sludge" fits to the investigated dredged materials, because they are more comparable in composition and behaviour to soils like marsh clay, which is used as dike construction material on the North Sea. Moreover, the parameters for the evaluation are very restricted and appropriate not all of the properties, which are necessary for a comprehensive evaluation.

On this account, an additional evaluation of the dredged material has been performed according to recommendations for the use of marsh clay as dike cover layers, which are presented in the EAK 2002 (2007) as well. A total of eight parameters (including e.g. grain-size distribution, plasticity and organic matter) have to be checked, and afterwards the result of each parameter has to be classified as "well suited", "suited" and "limited suited" (Table 10). For a better ranking of the materials, each result got further a separate evaluation number (EN) with the range from zero till three. The principle behind this is quite simple: a better suitability gets a higher evaluation number. For example the parameter which is classified as well suited gets three points, whereas a parameter characterized as "limited suited" gets only one point. For results below the lowest limit value the evaluation number zero is assigned. Finally all evaluation numbers are summarized for each material (Table 11).

In total, the evaluation after marsh clay shows a better graduated ranking of the investigated dredged materials than the results of the previous used method does, although the classification of the points has been a bit difficult. Within this evaluation method, none of the five materials get at least the classification "limited suited" in all parameters, wherefore no material can be characterized as suitable for dike cover layers.

Especially the parameters water content, organic matter and dry-density are most problematic and achieve seldom the required limit values. Compared to the other investigated dredged materials, material S2 can be characterized as the most suitable material, followed by material M1 and M3. Again material D was rated worst.

Another validation-possibility for marsh clay has been developed by Weißmann (2003). Within this method, the parameters water permeability, degree of shrinkage, plasticity index and disintegration time are compared. Both the disintegration time and the plasticity index are the parameters with the main influence of the evaluation number, because the lowest value for the water permeability as well as for the shrinkage limit is given with 0.75, whereas for the plasticity index as well as for the disintegration time a minimum value of 0.2 is defined. From each of the four parameters an auxiliary parameter B1 till B4 (equations 6 - 9) is calculated, which finally results in the evaluation number N (equation 10).

Table 12. Suitability classes after Weißmann (2003)

Evaluation number (N)	Degree of suitability	Suitability class (SC)
$1.00 \geq N \geq 0.85$	Very well suited	1
$0.85 > N \geq 0.75$	Well suited	2
$0.75 > N \geq 0.65$	Suited	3
$0.65 > N \geq 0.50$	Limited suitability	4
$N < 0.50$	Not advisable	5

Table 13. Evaluation number (N) and suitability class (SC) with best (*) and worst (*) characteristics of each material

Material	M1	M2	M3	S2	D
B1 (k_f)*	0.870	0.958	0.935	0.935	0.970
B2 (t_{30})*	0.641	0.720	0.610	-	-
B3 (Vs)*	0.750	0.750	0.775	0.750	0.838
B4 (PI)*	1.000	1.000	0.660	0.860	1.000
N*	0.804	0.848	0.735	-	-
SC*	2	1-	3+	-	-
B1 (k_f)#	0.861	0.952	0.885	0.935	0.908
B2 (t_{30})#	0.624	0.683	0.610	-	-
B3 (Vs)#	0.750	0.750	0.750	0.750	0.750
B4 (PI)#	1.000	1.000	0.660	0.860	1.000
N#	0.797	0.836	0.719	-	-
SC#	2	2+	3	-	-

$$B1 = 0.7 - (\log(kf) + 4)/20 \quad (6)$$

$$B2 = 0.2 * \log(t_{30,V}) \quad (7)$$

$$B3 = 1.0 - 1.25 * (V_S - 0.05) \quad (8)$$

$$B4 = 0.3 + 2 * I_P \quad (9)$$

$$N = \sqrt[4]{B1 * B2 * B3 * B4} \quad (10)$$

According to the results of the evaluation number, five different suitability classes can be evaluated (Table 12). Materials which are characterized with suitable class 1 are very well suited, whereas a material with suitable class 5 is not advisable as dike construction material. Due to the fact that no disintegration time t_{30} could be calculated at CI = 0.8, the disintegration time at natural water content $t_{30,wn}$ was used. In Table 13 both the best (*) and the worst (#) results of the geotechnical investigation are presented.

In the evaluation method after Weißmann the highest evaluation number was achieved at material M2, closely followed by material M1. Both materials can be classified as “well suited” as dike cover layer with the given boundary conditions (e.g. $t_{30,wn}$ instead of $t_{30,w(v)}$). The application of material M3 as dike cover layer can be classified still as “limited suitable”, so all three materials could be used in dike constructions. The evaluation of material S2 and D might not performed through the missing disintegration data.

6. Conclusions

The geotechnical characterization of different fine-grained, organic dredged materials from the Baltic Sea area has been tested for the application in dike constructions. Thereby, the specialties as well as possible adaptations in the laboratory handling of dredged material have been elaborated and were presented in the paper. Further a range of disintegration tests has been performed, where major limitations could be observed. The following conclusions can be derived:

1. The mineralogical grain-size analysis should be carried out after the removing of organic matter and carbonate because of the agglomeration of organic matter and carbonate with fine particles. Further, the organic content has to be determined in an elemental analyzer because the lime content influences the results of the determination in a muffle furnace.
2. The water permeability test has to be performed with slow saturation (B-test) because the organic matter leads to a compression of the sample at a fast increase of pressure. As result lower water permeability can be observed.
3. For the Proctor compaction test a clearly defined approach for detecting the compaction parameters is essential, because of varying results at different drying temperatures. In addition, the complete drying with a rewetting afterwards should be avoided for laboratory analysis.
4. The use of disintegration tests for determining the aggregate stability under static loading cannot be used for dredged material as yet, because major limitations in the testing procedure as well as in some boundary conditions occur. This includes, among other things, the mesh size compared to the agglomeration size, the sample preparation with drying and wetting and the non-existing dependency of increasing disintegration time with increasing water content. So further adaptations for the use of such test facility has to be investigated.
5. The applicability of fine-grained dredged material for dike constructions has been tested with evaluation methods after EAK 2002 and Weißmann, whereby two evaluation methods for marsh clay was chosen. After Weißmann (2003), two dredged materials could be characterized as “well suited” for the use in dike cover layers, but with some restrictions in the evaluation process (e.g. the use of $t_{30,wn}$ instead of $t_{30,w(v)}$).
6. The results of the geotechnical characterization and the aggregate stability investigation show the specialty of fine-grained dredged material and that there is a necessity of adaptations. The main challenge for the use of cohesive dredged material in dike construction is the high organic and water content, which influence important properties in laboratory analysis as well as in construction and post processing handling.

Nomenclature

A, *B*	= Auxiliary parameters
c	= cohesion
CI	= Consistency index
c_u	= Initial shear strength
DD	= Dry density
EN	= Evaluation number
kf	= Water permeability
LC	= Lime content
LL	= Liquid limit
N	= Evaluation number
OD	= Proctors density
OM	= Organic matter
φ	= Angle of friction
PI	= Plasticity index
PL	= Plastic limit
SL	= Shrinkage limit
TOC	= Total organic carbon
$t_{30(w)}$	= Disintegration time
Vs	= Degree of shrinkage
w	= Water content
w_n	= Natural water content
w_{opt}	= Optimum water content
Z(t)	= Disintegration number

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