LIFE02 ENV/B/000341

Development of an integrated approach for the removal of tributyltin (TBT) from waterways and harbors:
Prevention, treatment and reuse of TBT contaminated sediments

Task 3553: Reuse of sediments
Geotechnical evaluation of clean sediments
Final report November 2004

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Executive summary.

The main objective of the TBT Clean project was to turn organotin polluted sediments into (acceptably) clean material suitable for beneficial reuse. In order to clean the sediments, i.e. to remove the organotin compounds, various techniques have been evaluated, as described in the Task 3550 Reports ‘Treatment of Sediment’. However the objective of a treatment technology is to remove the organotins, it will also have an impact on the mineralogical composition and nature of the material, hence on the geotechnical behaviour of the material.

In this report two treated sediments have been evaluated geotechnically:

- the lagooned and bioremediated sediments from dredging location 1.5 (lowest pollution degree, see Task 3550 report);
- the sediments treated by chemical oxidation (and afterwards mechanically dewatered), also from location 1.5.

Various geotechnical tests have been carried out on these treated sediments. It has been found that the bioremediated sediments show the most favourable geotechnical quality. The structure of this sediment during bioremediation is altered in such a way that it behaves more like a loamy sand. It can be compacted to a high degree, its bearing capacity is high, and its internal cohesion is sufficient to create sloped constructions.
1. Introduction.

The main objective of the TBT Clean project was to turn organotin polluted sediments into (acceptably) clean material suitable for beneficial reuse. In order to clean the sediments, i.e. to remove the organotin compounds, various techniques have been evaluated, as described in the Task 3550 Reports ‘Treatment of Sediment’. However the objective of a treatment technology is to remove the organotins, it will also have an impact on the mineralogical composition and nature of the material, hence on the geotechnical behaviour of the material.

In general, dewatered dredged sediments are being reused for low-profile construction purposes, such as backfill material, dykes, embankments, liner material for landfills and intermediate landfill covers, etc.

First of all, depending on local legislation, the treated sediments should comply with the local imposed chemical criteria. In the framework of this TBT Clean project, the VITO (Flemish Institute for Technological Research) has drafted a framework for the reuse of sediments with organotin compounds, based on environmental and human risk evaluations. VITO is the institute that also derived all current pollution standards now being applied in the Flemish legislation on Soil Remediation (VLAREBO) and re-use of (former) waste materials.

The minimal treatment, in order the sediment should be ready for reuse, is dewatering. Therefore geotechnical evaluation of the initial dredged sediment is not meaningful as it will never be applied as such.

In this report two treated sediments have been evaluated geotechnically:

- the lagooned and bioremediated sediments from dredging location 1.5 (lowest pollution degree, see Task 3550 report);
- the sediments treated by chemical oxidation (and afterwards mechanically dewatered), also from location 1.5.

Sufficient sediments obtained by the pilot scale chemical oxidation test have been dewatered by means of the bench scale filter press that was constructed for this project (see figure 1). As a flocculant, 3 % lime was used.

Various soil mechanical tests have been carried out on these materials in order to make a generic evaluation of the geotechnical boundary conditions with respect to their reuse.
2. Soil mechanical tests.

A set of laboratory scale soil mechanical characterization tests have been carried out on both treated sediments samples. Table 1 mentions these tests, the test procedure applied and the information gained by these tests. Most of the simple tests have been carried out in the DEC laboratory, with own test equipment. Other specified tests have been carried out by Labo Devlieger (B).

Table 1: Soil mechanical tests applied on the treated sediments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Testing procedure</th>
<th>Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry matter content</td>
<td>CMA 2/II/A.1</td>
<td>the water content strongly influences the rheological behaviour of the sediments.</td>
</tr>
<tr>
<td>Organic matter content</td>
<td>ASTM D 2974</td>
<td>The organic matter content can influence the bearing capacity of the treated sediments.</td>
</tr>
<tr>
<td>Lime content</td>
<td>NEN 5752</td>
<td>The lime content gives information on the compatibility of the sediment with binders</td>
</tr>
</tbody>
</table>
such as cement.

<table>
<thead>
<tr>
<th>Method</th>
<th>Standard</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Methylene blue value</td>
<td></td>
<td>This test, in addition to the PSD, gives information about the active clay content, which is important in case the sediments should require lime stabilization.</td>
</tr>
<tr>
<td>Particle Size Distribution (PSD)</td>
<td>BS 1377</td>
<td>The particle size distribution, in particular sand content, is an important parameter as it will influence the geotechnical behaviour of the product at a certain water content.</td>
</tr>
<tr>
<td>Atterberg limits</td>
<td>BS 1377</td>
<td>These parameters yield information of the rheological behaviour (liquid, plastic) of the material in function of its water content, hence gives information how far the material should be dewatered in order to get a certain rheological behaviour.</td>
</tr>
<tr>
<td>Shear strength</td>
<td>CMA/2/II/A.4</td>
<td>The shear strength is a simple test giving information on the internal cohesion of the material when used for low performance applications such as dyke bodies.</td>
</tr>
<tr>
<td>Hydraulic permeability</td>
<td>Falling head method</td>
<td>The permeability of the compacted material gives information on the possibility of using the compacted sediment as liner for landfill applications. It will also help to predict risk and rate for leaching of residual pollutants from the reused sediments towards the groundwater.</td>
</tr>
<tr>
<td>Californian Bearing Ratio</td>
<td>ASTM D 1883-99</td>
<td>The Californian Bearing Ratio (CBR) is a measure for the bearing capacity of the compacted sediment at a certain moisture content.</td>
</tr>
<tr>
<td>Triaxial test</td>
<td>NEN 5117</td>
<td>This test gives information on the cohesion and stability of the material when used in any application and under different loads of surcharge, e.g. for backfill purposes, dykes,…</td>
</tr>
<tr>
<td>Long term deformation</td>
<td>ASTM D 2435-90</td>
<td>A long term compressibility test gives an idea of the creep behaviour of the material on the long term, which is important for reuse of high constructions (dykes, embankments,…).</td>
</tr>
</tbody>
</table>
Optimal Proctor BS 1377
The Proctor test determines the optimal moisture conditions for compaction of the materials when reused for backfill etc.

3. Discussion of results.


The basic characterization of both treated sediments are given in table 2 below.

Table 2: Characterization of treated sediments.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bioremediated sediment</th>
<th>Chemically oxidised and dewatered sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content w (%)</td>
<td>24</td>
<td>56</td>
</tr>
<tr>
<td>Dry matter content DMC (%)</td>
<td>80.6</td>
<td>64.1</td>
</tr>
<tr>
<td>Wet density (kg/dm³)</td>
<td>1.96</td>
<td>1.64</td>
</tr>
<tr>
<td>Dry density (kg/dm³)</td>
<td>1.58</td>
<td>1.06</td>
</tr>
<tr>
<td>Particle Size Distribution (figure 2)</td>
<td>sand (%)</td>
<td>48</td>
</tr>
<tr>
<td></td>
<td>loam (%)</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>clay (%)</td>
<td>29</td>
</tr>
<tr>
<td>Hydraulic permeability (m/s)</td>
<td>4.17 x 10⁻⁹</td>
<td>1.56 x 10⁻¹⁰</td>
</tr>
<tr>
<td>Initial CBR (%)</td>
<td>5.6</td>
<td>0</td>
</tr>
<tr>
<td>Shear strength (kPa)</td>
<td>77</td>
<td>36</td>
</tr>
<tr>
<td>Organic matter content (% on DM)</td>
<td>7.2</td>
<td>3.5</td>
</tr>
<tr>
<td>Lime content (% on DM)</td>
<td>18.4</td>
<td>15.3</td>
</tr>
<tr>
<td>Methylene blue (% on DM)</td>
<td>1.14</td>
<td>0.51</td>
</tr>
</tbody>
</table>
3.2. Evaluation of optimal Proctor.

The optimal Proctor is the water content (range) at which the material can be optimally compacted. In order to determine the optimal Proctor the sediment is dried or moistened to various water contents, then compacted in a Proctor mould (with standard compaction energy according to ASTM D 698-00), and via weighing of the mould the wet density is determined. From the wet density the dry density is calculated as:

\[ \gamma_d = \gamma_n / (1 + w) \]

with:

- \( \gamma_d \) the dry density in kN/m³;
- \( \gamma_n \) the wet density in kN/m³;
- \( w \) the water content (%).

The relation \( \gamma_d \) vs. \( w \) is set out in a curve. This is done for both treated sediment types in figure 3.
Figure 3: Proctor curve of treated sediments.

From the optimal Proctor test it can be seen that the optimal water content \( w \) in order to obtain the maximal compaction is around 18% \((\approx 85\% \text{ DMC})\) for the bioremediated sediment and 15% \((\approx 87\% \text{ DMC})\) for the oxidized and dewatered sediment. The optimal Proctor points are imported as the sediments should be maximally compacted when used in a construction work. Therefore the water content should be adapted to the optimal Proctor water contents before the sediments are applied.

Generally, sediment or soil compacted to its maximum density is most geotechnically stable (e.g. highest bearing capacity, internal cohesion,…) compared to soil that has not been compacted to its maximum Proctor density. It is also known that the long term deformation (consolidation) of the sediment will be less when compacted to its maximum density.

3.3. CBR-evaluation.

In addition to the Proctor testing, the bearing capacity was evaluated via CBR in function of the water content. The results can be found in figure 4.
As expected, the CBR values for both material are relatively high at lower water contents. For the bioremediated sediment it is observed that if the water content is too low, the CBR value is relatively low compared to the peak observed in the curve. This is due to the fact that optimal compaction in the Proctor mould was not achieved (see Proctor testing) and a further compaction-deformation (penetration) occurs when the CBR cylinder is put on the material.

It is observed now that the maximum CBR value is achieved around a water content of 14 % for the bioremediated sediment, and around 8 % for the oxidized and dewatered sediment. These values are slightly lower than the optimal Proctor values.

In order to have the best compromise between maximum compaction and maximum bearing capacity the average water contents from both tests should be applied, being 16 % for the bioremediated sediment and 11 % for the oxidized and dewatered sediment.

Figure 5 shows the CBR apparatus and its attributes in the DEC laboratory.
3.4. Consolidated undrained triaxial tests.

The tri-axial tests were carried out according to the standard NEN 5117. From this test the strength parameters $C'$ (internal cohesion shear strength) and $\varphi'$ (internal angle of friction) can be determined. These parameters are the basic parameters used in stability calculations, e.g. when sliding circles are evaluated when the material is used in sloped constructions (dykes, hills,…). The triaxial apparatus of Labo Devlieger is shown in figure 6.

The tests have been carried out in threefold. The obtained average values from the tests are given in table 3.
Table 3: Results of the tri-axial tests.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Bioremediated sediment</th>
<th>Chemically oxidised and dewatered sediment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cohesion C’ (kPa)</td>
<td>11.8</td>
<td>18.4</td>
</tr>
<tr>
<td>Internal friction angle φ’ (°)</td>
<td>32.1</td>
<td>22.6</td>
</tr>
</tbody>
</table>

From these results it can be concluded that the sediments behave as loamy to clayey soil.

3.5. Long term deformation tests.

The long-term deformation tests have been carried out at labo Devlieger by means of a standard soil oedometer, according to the standard ASTM D 2435-90.

The long-term deformation or consolidation of a soil or sediment when used in engineering purposes is the deformation (often settlement) the material undergoes after being installed...
and compacted. When used in a construction (dyke, embankment,…) it will be envisaged to compact the sediment to its maximal density, i.e. at its optimal Proctor point. However, the mechanical compaction – e.g. by means of a vibrating roller – is only a short term compaction energy input. After being installed the material will further suffer compaction under its own weight, in particular in high constructions of several meters or more. Compaction under own weight is a slow but steady process, and is mostly caused by consolidation. Consolidation is the process in which the pore water between the mineral grains evacuates due to its internal pressure caused by the weight of the above stored material. Macroscopically, consolidation results in settlements of the construction with time (months to years).

In order to estimate the long-term deformation behaviour it is therefore necessary to simulate this consolidation in an accelerated way. This can be done in an oedometer (see figure 7), in which a small sample of the sediment is compressed and the deformation (strain) is measured with time. The data derived from this test, such as the compressibility factor, can be used to estimate settlement (and the settlement in function of time) of larger constructions made of the sediment.

Figure 7: Oedometer at labo Devlieger.
The compressibility factor C has been derived by several load increments on the sediment samples. The loads applied were 20, 40, 80 and 160 kPa, which corresponds to a surcharge of about 1.25, 2.5, 5 and 10 m of material.

Both sediments have been tested.

The compressibility factors are given in table 4.

3.6. Atterberg limits.

The Atterberg limits give an idea of the texture based rheologic behaviour of the sediment. The water content at which the transition between the solid and plastic behaviour occurs is called the plastic limit \( w_p \), and the water content at which the transition between plastic and liquid behaviour occurs is called the liquid limit \( w_L \). The water content range between both values is called the plasticity index \( I_P \). The higher the value of \( I_P \) the finer (more clayey) the texture of the sediment is. With the option of reuse of sediments in mind, in order to prevent plastic settlements of the sediments, the water content at application should be at least lower than the plastic limit. The liquid limit has only importance for dredging operations.

The Atterberg limits of both treated sediments were derived according to BS 1337; the results are given in table 5.
It is clear that the bioremediated sediment, probably due to oxidation effects and hence physicochemical changes in soil structure, behaves more as a loamy sand, while the filter cakes from the chemically oxidized sediment behave like loam.

4. **Field test: compaction and plate test.**

In order to evaluate the geotechnical behaviour in the field small test fields were made by wooden boxes in which the biodegraded sediment was compacted. No sufficient sediment was available from the chemical oxidation tests to carry out a similar test.

The test fields were 1.2 by 1.2 m wide, and 60 cm deep. The boxes were placed on a hard concrete slab. In these boxes the biodegraded sediment was compacted at its natural water content (24%), which is slightly above the optimal water contents derived in the Proctor and CBR evaluation. Compaction was carried out with a vibrating manual compactor, as illustrated in figure 8. During compaction it was noticed that a small amount of water was expelled from the sediments. The sediments after compaction are shown in figure 9.

After compaction, the sediment was allowed to accommodate for one week. During this week the sediment field was covered with plastic to prevent evaporation or penetration of water. After this week the plate tests were carried out (in threefold) and the water content of the sediment determined. The average water content of the sediment compacted in the field was 21.2%, which is closer to the optimal water content derived in the laboratory tests.

Plate tests with a small plate (200 cm²) were carried out according to the M1 Compressibility modulus determination standard. Figures 10 and 11 illustrate the test box as well the plate test and displacement measurement. Table 6 shows the results of one of the plate tests.

The compressibility moduli derived were very good: between 16.2 and 21.5 M Pa, with the average of 17.8 M Pa. It can be concluded that the bioremediated sediment is very suitable for construction purposes such as backfills, embankments and dykes.
Figure 8: Compaction of the sediment in the test fields.

Figure 9: The sediments after compaction.
Figure 10: View on the small plate during the plate test.

Figure 11: View on the small test field.
Table 6: plate test results.

### Plate test bioremediated sediment TBT Clean

**Size plate** 200cm²

**Date testing** 22/10/2004

#### First load step

<table>
<thead>
<tr>
<th>Pressure (M Pa)</th>
<th>Dilatometer 1 (mm)</th>
<th>Dilatometer 2 (mm)</th>
<th>Dilatometer 3 (mm)</th>
<th>Average settlement (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0,02</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0,00</td>
</tr>
<tr>
<td>0,05</td>
<td>0,22</td>
<td>0,21</td>
<td>0,26</td>
<td>0,23</td>
</tr>
<tr>
<td>0,1</td>
<td>0,54</td>
<td>0,59</td>
<td>0,57</td>
<td>0,57</td>
</tr>
<tr>
<td>0,15</td>
<td>0,99</td>
<td>1,15</td>
<td>0,99</td>
<td>1,04</td>
</tr>
<tr>
<td>0,2</td>
<td>1,32</td>
<td>1,5</td>
<td>1,4</td>
<td>1,41</td>
</tr>
<tr>
<td>0,25</td>
<td>1,95</td>
<td>1,94</td>
<td>2,02</td>
<td>1,97</td>
</tr>
<tr>
<td>0,35</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0,45</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Settlement (mm) first load

![Graph showing average settlement mm first load](image)

<table>
<thead>
<tr>
<th>M1 (M Pa)</th>
<th>Embankment</th>
<th>19,62</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Subfoundation</td>
<td>17,22</td>
</tr>
<tr>
<td></td>
<td>Foundation</td>
<td>N.D.</td>
</tr>
</tbody>
</table>
5. Conclusions.

Various geotechnical tests have been carried out on two type of treated sediments: the bioremediated sediments and the filter cakes of the chemically oxidized sediments. It has been found that the bioremediated sediments show the most favourable geotechnical quality. The structure of this sediment during bioremediation is altered in such a way that it behaves more like a loamy sand. It can be compacted to a high degree, its bearing capacity is high, and its internal cohesion is sufficient to create sloped constructions.
6. References.

www.vito.be

ASTM standards