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

A LUSTRUM OF VALORISATION OF CONTAMINATED SEDIMENTS FROM THE PORT OF DUNKIRK (FRANCE).

Sofie Herman[1], Alain Pieters[2], Daphné Glaser[3], Pascal Gregoire[4], Christophe Priez[5], Didier Desmoulin[6], David Guglielmetti[7]

[1,2,3] *Envisan NV, member of Jan De Nul Group, Tragel 60, 9308 Hofstade Aalst – Belgium, sofie.herman@envisan.com, alain.pieters@envisan.com, daphne.glaser@envisan.com,*
[4] *Grand Port Maritime de Dunkerque (GPMD), Terre-plein Guillain, B.P. 6 534, Dunkirk, 59386, France, pgregoire@portdedunkerque.fr*
[5] *Direction Technique COLAS Nord Picardie, 197 rue du 8 mai 1945- F 59 491 Villeneuve d'Ascq, France, christophe.priez@colas–np.com*
[6] *Direction Technique COLAS Routes France, 4 rue Jean Mermoz- Bâtiment A- F 78772 Magny les Hameaux, France, didier.desmoulin@colas.com*
[7] *Directeur Marketing et Innovation Ciments Calcia et Unibéton, Les technodes, 78 931 Guerville, France, dguglielmetti@ciments-calcia.fr*

Abstract. The Port of Dunkirk is responsible for the maintenance dredging and disposal of the maritime fairways, canals and docks within the perimeter of the Grand Port Maritime de Dunkerque (GPMD). Sediment quality surveys were conducted and indicated variable degrees of contamination of the sediments in addition to which the official 'GEODE' threshold levels of the French regulation for some heavy metals were exceeded. Based on that investigation, the permit-application concluded that a mere open-water disposal in the North Sea is not permitted. Therefore the GPMD has taken the opportunity to invest into a newly built 6 hectares treatment facility and a large valorisation project for contaminated sediments. By means of natural dewatering the hydraulically dredged sediments are dehydrated in the treatment facility and ready to be valorised in a 500 m confinement dike along the 'Canal des Dunes' within the Port area. The last 5 years the GPMD has valorised with this project more than 200.000 m³ of contaminated sediments dredged from its docks in the eastern part of the harbour. Recently the Port has invested in two full scale innovative demonstration projects for the beneficial re-use of contaminated sediments: The first project was executed in 2012 where the contaminated sediments were valorised in a new 700 meter long road in the harbour of Dunkirk (Route Freycinet 12). This project includes the preliminary testing for the mixture of the sediments in order to obtain the equivalent quality as for standard road works (in collaboration with Colas). A second project has been executed in the summer of 2013 and consists in the fabrication of 110 breakwater revetment blocs with a volume of 4 and 6 m³. For this project a maximum amount of sediment has been re used in the blocs. 2 supply locations are foreseen to be able to execute reparation works on the cores of the dikes for the coming 4 years. In the end of September 2013, 4 blocs have already been installed on the "Digue des Huttes" in Dunkirk (in collaboration with CTG). All technical specifications were achieved in the projects. Beneficial re-use of dredged material is currently in the process to get a legal framework in France.

Keywords: Dredged material, valorisation, contaminated sediments, dike construction, concrete, road construction

1. Introduction

The Grand Port Maritime de Dunkerque (GPMD) is located on the North Sea shore with a coast line length of more than 15 km. It is the third biggest coastal sea port in France, close to the rail of separation of traffic crossing the Strait of Pas de Calais on the busiest Seaway in the world with no less than 600 ships per day. The accumulation of sediment causes the reduction of the draught necessary for navigation of cargo ships and tankers of high capacity which requires a permanent dredging of the channels (sandy sediments), of the front ports (very sandy sediments) and the docks (fine polluted sediments).
The sand is stored and marketed for embankments and building materials. Disposal at sea was practiced for a

Table 1. French standards for reference levels for dredging and disposal of sediments

Contaminants	Thresholds (mg/kg of dry sediment)	
	Standard N1	Standard N2
As	25	50
Cd	1.2	2.4
Cr	90	180
Cu	45	90
Hg	0.4	0.8
Ni	37	74
Pb	100	200
Zn	276	552
PCB (total)	0.5	1
PCB congener 28	0.025	0.05
PCB congener 52	0.025	0.05
PCB congener 101	0.05	0.1
PCB congener 118	0.025	0.05
PCB congener 138	0.05	0.1
PCB congener 153	0.05	0.1
PCB congener 180	0.025	0.05

Table 2. Sediment characteristics

Dry matter (DM)	45 - 50.5 %
Organic matter (OM)	9.7 - 12.3 %
Clay content <2 µm	17 - 27 %
Sand content >63 µm	35 – 15 %

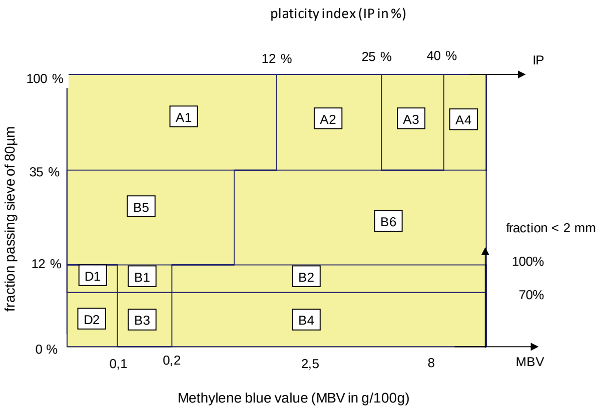

Fig 1. French standard NF P 11-300: classification of materials used in the construction of embankments and subgrade road infrastructure.

long time for sediments, but the regulation of the Ministerial Decree of June 14th, 2000 (Arrêté, 2000) imposes a stricter management of sediments and forbids this disposal for polluted sediments that must transit on shore into secure systems. The GPMD has taken the opportunity of investing in the construction of pre-treatment centre for the dehydration of their sediments and therefore no longer dispose the contaminated dredged sediments from the harbour at sea with thresholds > N1, the level of concentration of contaminants underneath which disposal at sea is authorised and above which a complementary study is imposed (Arrêté, 2000). In Table 1 the thresholds are presented for level N1 and level N2 (the level of concentration of contaminants above which sediments should be treated on land.

Of the 4000000 m³ dredged every year by the port of Dunkirk, 500000 m³ are too polluted to be disposed at sea. Therefore the port of Dunkirk has invested in the past 5 years in 3 different valorisation projects. The main goal for the Port of Dunkirk is to establish demonstration projects of recycling contaminated materials into useful products for the harbour in order to avoid deposit of the sediments in landfills which implies higher costs. Due to the environmental follow up of the projects, these full scale projects are an example for institutions and industries to show that the future lies in green environment and starts with your own development.

2. Sediment characteristics

The contaminated sediments dredged in the last 5 years for this project all originate from the East harbour of Dunkirk. These sediments (average characteristics given in Table 2 are (very) fine-graded; they have high water content and the clay content is variable.

The geotechnical behaviour according to the GTR (Guide Technique Routier) (LCPC Sétra, 1992) can be compared with A1 soils for the less plastic and with A3 soils for clayey soil. The general classification of the soils according to the French standard NF P 11-300 can be found in Fig 1. Often the sediments have an increased organic matter content which may interfere with the setting of hydraulic binders. Their geotechnical classification according to the GTR subsequently is F11 or F12 (LCPC Sétra, 1992).

3. Valorisation of contaminated sediment in a dike

From 2009 till 2013 each year a volume of 20000 m³ of lagooned sediments were re-used in a 500 meter dike along the ‘Canal des Dunes’ in the Port of Dunkirk. This project included the civil construction works, the covering with top soil and the plantation of the slopes with specific vegetation. Piezometers were installed in order to follow the possible impact of the dike on the quality of the underlying groundwater table.

The dike is designed with a variable width at the base and with a variable slope between 12/4 and 6/4. The height varies between 5 and 7 meters above the natural terrain. The dehydrated sediments are transported with tip up trucks from the pre-treatment centre to the dike. There the sediments are spread with a bulldozer following the marks put in place by the surveyor. Since no specific compaction was required, no supplementary compaction has been done. Since the final design of the dike was fixed by the Port

Authorities, the dry matter content to be obtained after lagooning was determining for the stability of the dike (the geotechnical characteristics of the sediment being fixed). The dike stability was calculated with the D-sheet Piling calculation program using the cohesion and internal friction angle measured by means of a CU triaxial test on lagooned Dunkirk material after proctor compaction.

Once the dike was constructed and covered with 25 cm of non-contaminated topsoil, the first season the slopes were planted with the following endemic plant species:

- 20% Creeping Willow (330 pieces) (Lat. *Salix repens ssp arenaria*)
- 20% Black Elder (333 pieces) (Lat. *Sambucus nigra*)
- 50% Common Sea-Buckthorn (820 pieces) (Lat. *Hipphophae rhamnoides*)
- 10% Field Maple (165 pieces) (Lat. *Acer campestre*)

The dike has been the subject of an environmentally landscaped construction based on the value of re-use of contaminated sediments. The added value of the dike was to create a biodiversity by integrating specific species which are part of the ecological environment of the sector.

During the maintenance and aftercare period, the plants suffered from exceptional circumstances such as very high wind speed and very dry weather conditions. Therefore, some of the plant species didn't survive, one species being more sensitive than the other (e.g. Creeping Willow vs. Common Sea-Buckthorn). It was then decided to plant only sea-Buckthorn and Field Maple (80%/20%) the next growing season. However, after three years of plantations and ecological monitoring no abnormality was detected in the works in terms of stability.

Fig 2. Sediment dike under construction

Fig 3. Dike after plantation of vegetation (first season)

Fig 4. R&D tests with different mixtures as cover layer

In order to investigate effect of wind and water erosion on the thickness of the protective top soil layer the thickness was measured in function of time. No degradation of this layer was observed. However, a fence was installed around the dike in order to prevent damage of the top soil layer on the slopes by the circulation of motor cycles and quads.

The dikes have also been subject to a piezometric monitoring to qualify the changes in the groundwater table and to check the environmental impact of the dike. The results confirm the absence of significant impact on the groundwater that remains consistent with the prediction made in modelling phase at the time of impact assessment.

In order to increase the volume of sediments to be stored in the dike R&D tests were started in 2012 to check the suitability of other materials as an alternative for classical good quality top soil which is hard to find in the Dunkirk region. During the test the growth of the Common Sea Buckthorn plants is evaluated in function of the different substrate mixtures tested. The scenarios tested are: 100% classic top soil, 100% lagooned sediment, different mixtures of sediment with compost and different mixtures of sediment with peat. For the moment the growth of the Buckthorn on the sediment (100%) and on the mixture of sediment with peat is comparable to the one growing on top soil. In a next step the resistance to erosion has to be checked on a pilot plot on site.

4. Valorisation of contaminated sediments in sub base and base layers for the reconstruction of the road "Freycinet 12" in the port of Dunkirk.

The re-use of contaminated sediments from the Port of Dunkirk in road structures was initiated as early as 2002. On that date, the Port started cooperation with the Ecole des Mines de Douai and various partners, including the company COLAS in order to design alternative materials for stabilised sub base road layers.

After a first project phase of lab scale tests, in 2005, a pilot test was carried out on a 300 m² plot where a 50 meter long road was constructed using treated sediments. The objective was to verify the industrial feasibility of the entire process which included the following targets:

- Application of a thin layer of the sediment for complete drying
- A grain size correction by mixing the sediment with sand in order to obtain a material with a better grading. Results can be found in Fig 5. It is in no way a dilution of the pollution contained in the sediment but a search of geotechnical optimisation to create a usable material. The necessity for a grain size correction has been confirmed in the SETARMS project (Boutouil, 2013).
- A treatment with quick lime which contributes to the preparation of a treatable mixture with hydraulic binder. The application of the lime reduces the water content and flocculates the clay particles and reduces the organic matter content.
- A subsequent treatment with a hydraulic binder. The hydraulic binders were developed in a partnership between HOLCIM and COLAS and it was shown that it is possible to obtain soil T2 or T3 (view Table 3 for general French classification) with a granular mixture containing at least 30% of sediment.
- Protection of the road/pilot plot by a seal coat. First results showed no impact of this alternative with sediments and showed only a slight elevation compared to the thresholds for drinking water.

6 Months after the completion of the test, control of the mechanical strengths (Tensile strength Rit / Elasticity Modulus Eit) obtained on cores confirmed the results (Fig 6) of the laboratory study and exceeded the expectations to find only soils of class T2.

During the laboratory study the mechanical performance of the treated sediment/sand mixture gave a ranking in class S3 with a lower stiffness modulus. (red point on Fig 6). Normally the stiffness modulus is between 15000 and 30000 MPa. The mechanical performance measured on the cores of the pilot road plot confirms an average level S3 with a stronger stiffness modulus.

The 2005 experiment has demonstrated that the formulation of alternative road materials is possible

Table 3. French classification of soils regarding their mechanical performances (Tensile strength Rt and Elastic modulus E)

E MPa	2 000	5 000	10 000	20 000	40 000
Low limit of category			R_t MPa		
T5	0,97	1,50	1,93	2,35	2,60
T4	0,67	1,00	1,26	1,49	1,70
T3	0,52	0,73	0,90	1,05	1,20
T2	0,34	0,47	0,57	0,67	0,75
T1	0,19	0,26	0,32	0,38	0,43
NOTE The Table gives the values of R_t and E used to draw the curves limiting the categories T5, T4, T3, T2 and T1.					

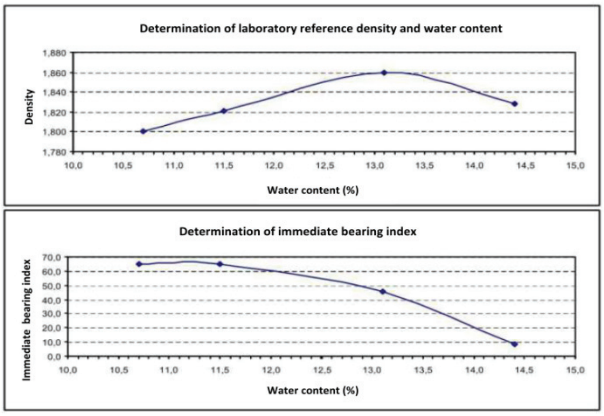

Fig 5. Proctor curve and IPI-curve of sediment after treatment

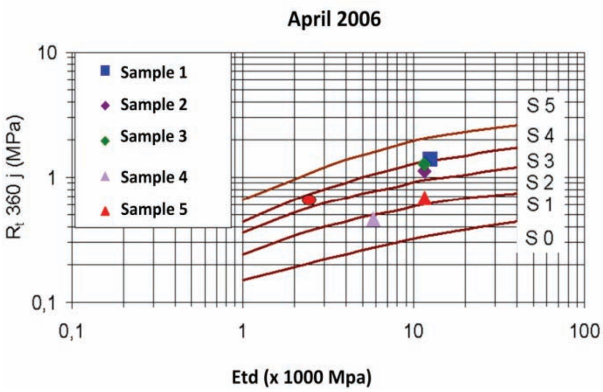

Fig 6. Direct tensile strength (Rt in MPa) versus the Elastic modulus (Etd in GPa) results of the lab scale results and of the cores of the 2005 pilot test road (red dot)

Fig 7. Treatment of the sediments on the Freycinet road

with sediment. The road has to meet the requirements of the French standard dimension criteria for roads constructed with the usual road materials. Following these results the Port of Dunkirk decided to continue in this way with industrial partners: ENVISAN for dredging and lagooning, and COLAS for the formulation of road materials using this resource.

In 2012, the Port of Dunkirk decided to reconstruct the road ”Route du Quai Freycinet 12” serving the Ruby Company specialising in fuel trading.

The road structure is designed for 15 years of traffic with an average of 100 heavy good vehicles per day. The usual road structure drawn by the technical services of the Port for the tender requirements consists of 6 cm of hot mix asphalt on 40 cm of slag bound mixture on the sand platform.

Taking into account the results of its studies on the sediments dredged in October 2011, COLAS Nord Picardie proposed the following mechanically equivalent alternative road structure: 5 cm of high modulus bituminous concrete on 6 cm of EME (Asphalt concrete with high modulus) / 30 cm of material containing the contaminated sediment dredged and lagooned by Envisan on the sediments treatment platform. This solution consumes 1 m³ of sediment per 10 m² of roads. Thus, 450 m³ of dry sediment representing 1800 m³ of dredged sediments were used. An environmental plot on a surface of 100 m² was installed in order to collect any water percolation through the road structure.

4.1 Incoming geotechnical results

The lab study of 2012 gave results which were less optimistic than the ones of the 2005 study. The road mixture reached however a level of mechanical class T2 which was taken into account in the design of the road structure. The short term compressive strength reaches 1.3 MPa after 7 days and allows a correct trafficability for the normal operations on site. The stiffness modulus reaches in the long term more than 9000 MPa and the tensile strength becomes higher than 0.6 Mpa.

Cores extracted at 180 days show a very good cohesion of the material and the level of tensile strength is equal to the one obtained in the laboratory study.

Deflection measured at 60 days after implementing (average < 10 / 100th mm) is correct and shows the proper efficiency of the treated sediment-based layer.

4.2 Environmental monitoring results

The sediments used for the road were analysed according to the methodological guide for the acceptability of alternative materials in road construction (Setra, 2011)

The analysis confirmed the effectiveness of the treatment by bio remediation revealing no problems in organic pollutants level (BTEX, PCBs, THC, TOC, PAH) and heavy metals as given in Fig 8.

In accordance with this guide and the regulation applicable in France, leaching results according to NF EN 12457-2 tests reveal some problems for soluble fraction, sulphate and chloride in the sediment which find their origin in the marine environment.

Tests in partnership with Holcim were conducted on the treated mixture laboratory specimens that show a significant reduction in the soluble fraction by adaptation of the hydraulic binder.

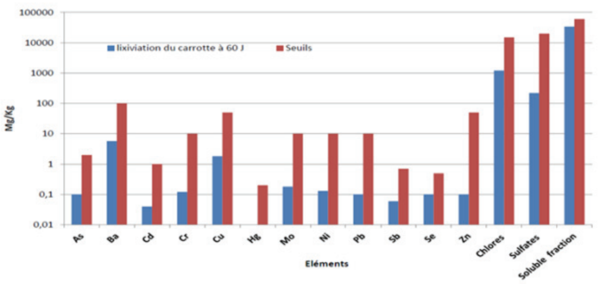

Fig 8. Leaching results on core material after 60 days (blue) compared to the limit (red) expressed in mg/kg

Analysis of the percolated water on the plot helped to verify the efficiency of blocking the soluble fractions by treatment with specific hydraulic binder with close analyses of the A 1 threshold of the law of water.

After finalising the works, analyses of the percolated water in the groundwater, in the nearby dock along the Route du Quai Freycinet 12 and in the piezometer are conducted every month during the first year and six-monthly the following 2 years. One year after the works, no remarkable changes have been detected in the three monitoring points.

5. Valorisation of contaminated sediments in concrete breakwater revetment blocks

In the spring of 2013 the Port of Dunkirk awarded the project for the fabrication of 110 breakwater revetment blocks (4 and 6 m³ volume) to Envisan. These blocks contain contaminated sediments earlier dredged in the Brocqaire channel and the dock 'Darse 6'. Prior to the valorisation of the contaminated sediments as partial replacement of the sand fraction in concrete, the sediments were lagooned and pre-treated. The concrete was fabricated in the concrete plant of Unibéton based on the formulation of the concrete given by Italcementi. The actual fabrication of the blocs and installation of the blocs on the breakwater of the eastern part of the Dunkirk harbour (Digue des Huttes) was executed within 2 months.

Contaminated (marine) sediments are often fine textured, have a fairly high sulphate content and/or have a rather well sorted grain size distribution and are therefore by definition not as such easily reusable in concrete. Indeed fine grained sediments are characterized by a high water holding capacity and, without pretreatment, fine sediments obstruct the classical feeding systems in concrete plants. The solution for this problem, developed and patented by the Italcementi group, is the pre-treatment of the lagooned sediments with ALIPRE®. This calcium Sulfoaluminate clinker (CSA) based binders is a ground sulfoaluminate-belite clinker, which main phases are: calcium sulfoaluminate, belite and calcium sulphate. One of the differences with ordinary Portland cement, is the formation of primary ettringite during the hydration when mixed with the sediments. The ettringite formed not only dries out the sediment (by capturing the water in the newly formed ettringiet crystals) but also dramatically changes the consistency of the sediment in the concrete plant.

After the treatment the sediment has a more sandy structure which is very favourable for the further processing of the sediment. After sampling of the sediments in December 2012 from the lagoons an elaborated lab scale study was conducted in order to adjust the pre-treatment step and the formulation for the concrete (lab study performed by Italcementi's R&D team at CTG). Already in 2010 Italcementi gained in depth experience on the valorisation of Dunkirk sediments in concrete during an elaborated lab scale test campaign and the pilot scale fabrication of 6 4m³ blocks, each with a different concrete formulation. The formulation from 2010 was adapted taking into account the specific geotechnical characteristics from the sediments sampled in 2012.

In July 2013 pre-treatment pilot scale tests were performed in Envisan's soil and sediment treatment centre in Ghent-Belgium on sediments with a comparable grain size.

During this pilot test the CSA dosage in function of the moisture content and grain size of the sediments; and the granulation of the sediment agglomerates after treatment was validated and optimized. With the experience obtained from the pilot scale tests the full scale treatment of the sediments was performed in early August 2013. The sediment treatment was done with a mobile installation as shown in Fig 9 and consisted in a screening of the sediment prior to the mixing with the CSA binder and finally the granulation of the mixture.

Subsequently a test run was performed with the treated sediments in the concrete plant of Unibéton at Calais. The test consisted in the fabrication of 3 m³ of concrete where the sediment was used as a partial substitution for the sand in the concrete (± 35% of the normal quantity of sand used in concrete). The critical parameters evaluated during the test run were the mixing energy, the workability and the compression strength of the concrete. Since all tests were satisfactory, the final fabrication of the 110 concrete blocks was started on the 27th of August and finished 12 days later. For the fabrication of the concrete blocks the harbour of Dunkirk put their own molds at the disposal of Envisan as shown in Table 4. The 4 and 6 m³ blocs are not armoured and only a hook is foreseen in order to facilitate the positioning of the blocs on the breakwaters. The first 4 concrete blocks have been installed in the beginning of September 2013 on the "Digue des Huttes" as shown in Fig 11.

The compression strength of the concrete obtained on full scale was largely above the required strength of30 MPa. After 28 days the compression strength obtained on all cylindrical test pieces was > 39 MPa (a C30/37 concrete was required). On average between 12

Fig 9. On site pre-treatment of lagooned sediments with the CSA additive.

Fig 10. Demoulding of the blocs on site

Table 4. Tender requirements for concrete

Tender technical requirements for the concrete
Concrete strength BHCA C30/37 (concrete Hors Champ d'Application: and therefore not subject to the concrete standard EN206-1)
Consistency: S4 (slump test)
Concrete for exposure to seawater
Cement according to NF P 15317 standard
Gravel according to NF P 18545 standard and max. D=20mm
W/C factor maximum 0.55
Admixtures according to NF EN 194-2
Water according to NF EN 1008
Amount of sediment in the concrete:12.5 - 20%

Fig 11. First concrete blocks containing contaminated sediments on the Digue des Huttes at Dunkirk (Sept. 2013)

and 20 W% of sediments was used in the concrete blocks which corresponds grosso modo to 0.5m³ of sediment (in situ/before dredging) per m³ of concrete.

6. Conclusions

The Grand Port Maritime de Dunkerque (GPMD) has invested the last 5 years into innovative solutions for the sediment contamination in their harbour. This resulted in 3 main projects for which the Port could re-use the sediments in an environmentally safe way.

1. The environmental dike was the first valorisation project in France. General legislation is not yet in

place to make the reuse of contaminated sediments applicable in all harbours nor with all kind of sediments. Severe feasibility studies should be carried out and a permit for a specific place and for specific types of sediments should be obtained for each project.

2. The road construction works with re-use of contaminated sediments have proven the workability and the fact that it has no impact on the environment.
3. Optimisation of the re-use of more types of sediments (fine/coarse/high or lower dry matter content) in more varieties of concrete applications is still in process.
4. Whatever kind of re-use of contaminated sediments is considered, elaborated studies of the sediments and the detected contamination in function of the end-product is necessary.
5. No general legislation in France is available for the re-use of contaminated sediments in civil construction works. Nor is there a standard for the re-use for waste in concrete applications. This is the missing link for re-use of contaminated sediments in France and for sure in many other countries.

Nomenclature

BTEX acronym for Benzene, Toluene, Ethylbenzene and Xylenes
PCB PolyChlorinated Biphenyl
THC Total HydroCarbon
TOC Total Oganic Carbon
PAH PolyAromaticHydrocarbons

References

Arrêté ministériel du 14 juin 2000 relatif à la protection des milieux marins et estuariens.

Boutouil Mohamed, 2013. Malo Le Guern-Lucile Saussaye-Walid Maherzi-Sédiments de dragage traités aux liants hydrauliques- Evolution du comportement mécanique à court et long termes. Recyclage et valorisation. N°41 spécial juin 2013.

CFTR-Sétra, 2007. Guide technique Traitement des sols à la chaux et/ou aux liants hydrauliques- Application à la réalisation des assises de chaussées.

LCPC Sétra, 1992. Guide Technique Réalisation des remblais et des couches de forme.

Sétra, 2011. Guide méthodologique Acceptabilité de matériaux alternatifs en technique routière- Evaluation environnementale.