Beneficial use of dredged sediments in road engineering

Methodological guide

Adapted from the French

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With the support of

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Foreword

This guide presents how dredged sediments can be beneficially used in road engineering with a view to sustainable development and to the protection of the environment and of populations. This is the result of research carried out by the Department of Civil and Environmental Engineering (DGCE) at the School of Mines of Douai for more than ten years on the theme of using dredged sediments. It is coherent with French regulations and the methodological framework (ADEME, 2010; SETRA, 2011) that prevailed at the time of the work. The proposed methodology was developed by the Ecole des Mines de Douai as part of France's SEDIMATERIAUX project and may be reviewed in the light of feedback received at the French national or European level.

The SedNet network (www.sednet.org) promotes since 2004 beneficial uses of dredged sediments, in a perspective of sustainable development and of circular economy. Road engineering is one of these beneficial uses, as it reduces both waste and mineral extraction.

This guide is not intended for use of sediments abstracted from a river system. It is only intended for harbour and canal dredgings, where restitution to river systems is usually not possible - at least economically.

Otherwise, it should be first considered to reintroduce them where the river system may need them, before considering any engineering use.

1. The issue of dredged sediments

1.1 Harbour sediments

Harbour structures are generally composed of basins with particularly high sedimentation rates, where dredging operations must be conducted to maintain the draft required for navigation. These dredging activities concern industrial and commercial ports as well as small and medium-sized harbour structures dedicated to fishing or pleasure activities. The largest volume of sediments dredged in France is generated by port structures on the North Sea Channel coast with 16.7 million tonnes of material. Next are the Atlantic and Mediterranean coasts with respectively 11.3 and 2.4 million tonnes of dredged sediments (CETMEF, 2012).

Depending on the risks they pose to the environment, dredged sediments can be either directed towards maritime or terrestrial management systems. In France, immersion is by far the main option for the management of dredged sediments, but this does vary from one maritime area to another, as the table below shows.

Table 1. Main management routes for dredged sediments in France (CETMEF, 2012)

Management options (%)	English Channel (%)	Atlantic (%)	Mediterranean (%)
Immersion	95.19	98.71	97.23
Beach nourishment	0.07	1.11	1.06
Deposit on land	4.72	0.16	0.96
Deposit at sea	-	0.02	0.75
Other options *	0.01	-	-

* *Dispersion of sediment by water injection, containment, embankment creation, use in harbour structures and landfills.*

Therefore, more than 95% of the sediments dredged on the three French maritime coasts are discharged at sea. Land deposit is the most common solution for non-submersible sediments. That method concerns about 5% of sediments dredged on the Channel-North Sea coast. Around the French coasts less than 1% of dredged sediment deposits are used for another purpose (Table 1).

1.2 Inland sediments (rivers and waterways)

Waterway sedimentation sources are diverse and specific to each waterway according to their uses, morphological characteristics and location. For example, soil erosion in watersheds is the main source of sediment for waterways. The waters of tributaries or agricultural or industrial urban discharges, regularly loaded with suspended matter, are secondary sources of sedimentation for the waterways. Other phenomena, such as the destabilisation of banks or the direct input of plant debris by the riparian forest, can participate in sedimentation of waterways but these occur under very particular conditions and represent negligible material contributions.

With 680 km of navigable waterways, of which 576 km are useful for commercial navigation, the Nord-Pas de Calais region has the densest the fluvial network in France (Figure 1).

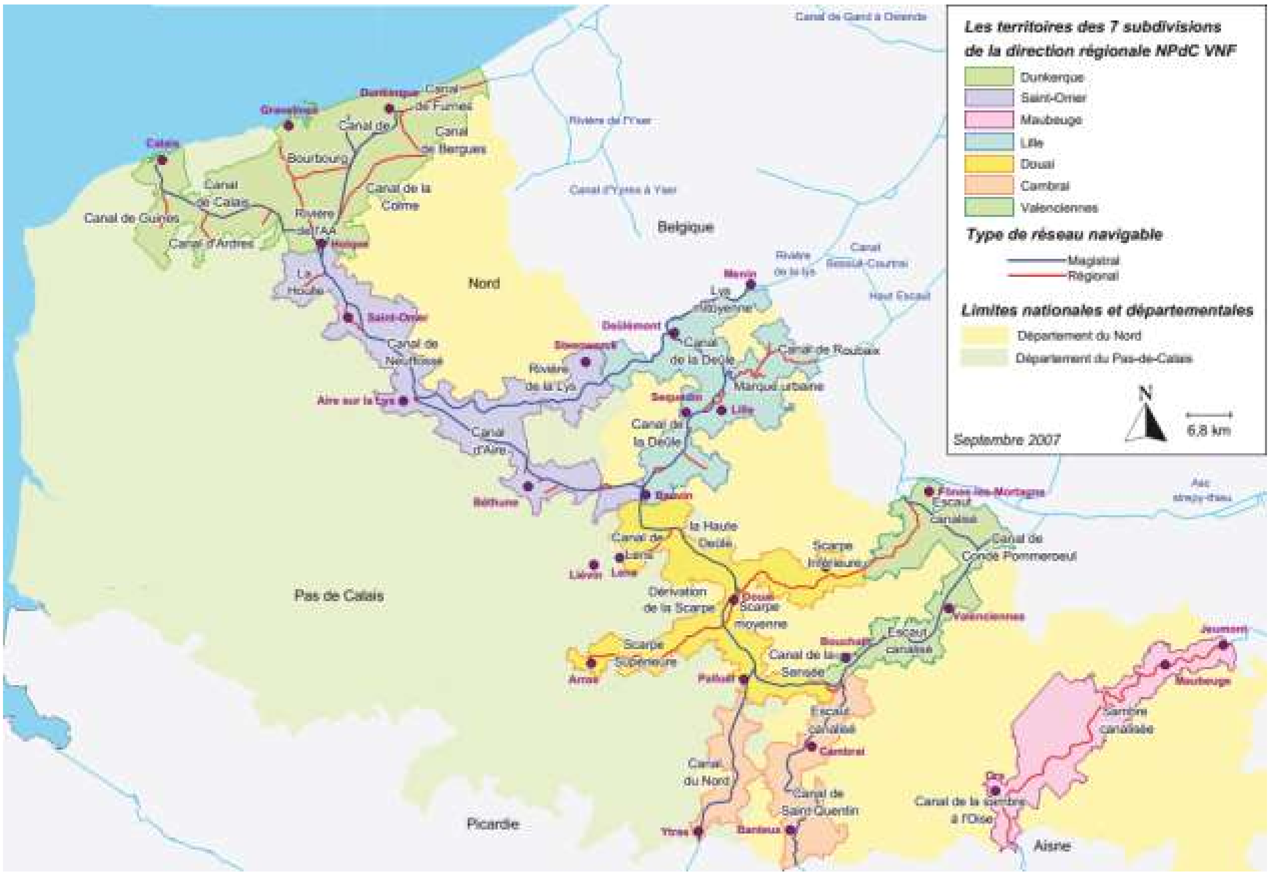


Figure 1. Navigable network of the Nord-Pas de Calais Regional Directorate of the French Waterways Board (VNF-SDRTD, 2009)

The Regional Master Plan for Land Disposal (VNF-SDRTD, 2009), developed by the Nord-Pas de Calais waterways agency in 2007, estimates that the total volume of sediment to be dredged over 20 years at approximately 8.5 million m^3. Depending on their physical and chemical properties, these sediments can be relocated in the following sectors:

- Resuspension of sediments
- Use as soil amendments, embankments and bank reinforcements
- Disposal: on confined or non-confined ground
- Landfilling

However, the physical (high level of fine particles) and chemical (presence of metallic trace elements and organic micropollutants) characteristics of these Nord-Pas de Calais waterway sediments currently hinder their beneficial use. At present, therefore, disposal is the main land-based management route for waterway sediments. The sediment volumes to be dredged from the main Nord-Pas de Calais waterways were estimated as part of the SDRTD (Figure 2). The estimates distinguish two large volumes for the different waterways:

- Volume to be dredged in 2007 to restore optimal conditions for navigation
- Volume to be dredged until 2027 to maintain canal draft

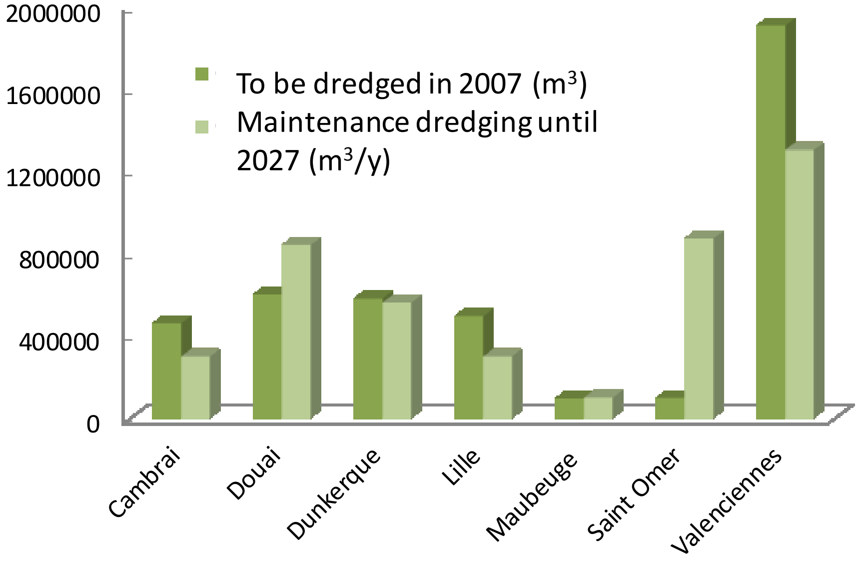


Figure 2. Estimate of sediment quantities to be dredged between 2007 and 2027 on the waterways of the Nord-Pas de Calais region (VNF-SDRTD, 2009).

2. Objectives of the SEDIMATERIAUX approach

With the goal of sustainable development, dredged sediments should be returned to their original environment, i.e. immersed or used for beach recharge. However, the strengthening of environmental regulations for dumping, land storage and landfilling of waste and regulatory incentives for using waste now raise the question of how to define the sustainable use of non-submersible sediments.

The SEDIMATERIAUX approach was started in 2009 by the Ministry of Ecology, Energy, Sustainable Development and the Sea, the Nord-Pas de Calais Regional Council, the Nord-Pas de Calais Prefecture, the CD2E and Ecole des Mines de Douai.

The SEDIMATERIAUX approach proposes operational solutions for on-land management of dredged sediments by:

- accompanying and guiding operators and project owners during the development of their projects,
- proposing a harmonised methodological and scientific framework for the on-land beneficial use of dredged sediments,
- identifying and developing channels suitable for all types of sediments coming from ports or canals,
- producing the scientific data necessary that will lead to changing French regulations.

3. Current practices for using dredged sediments in road engineering

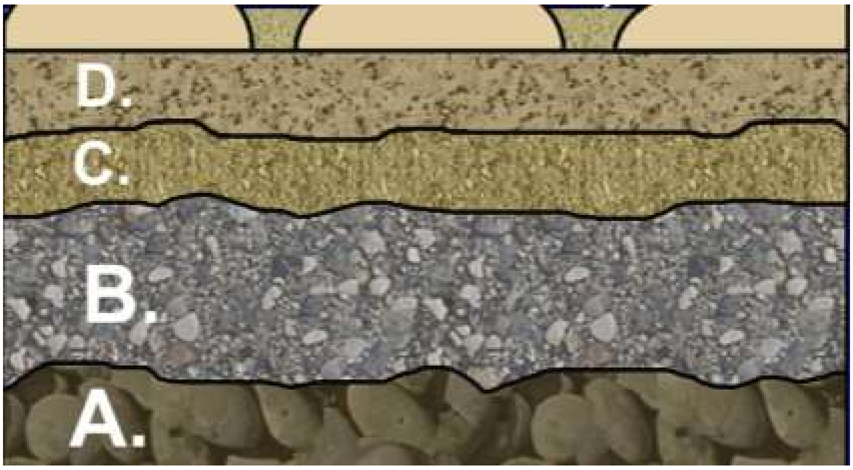
Public works need large amounts of minerals. Aggregate is one of the main resources for this sector. Aggregate is regularly used in the manufacture of concrete and road surface. Most of the aggregates produced in France come from land-based quarries or from alluvial deposits; these resources are being depleted. Therefore, we can develop the beneficially use of aggregated dredged sediments to meet the growing needs of the public works sector and in particular in roads.

The French Order of 30 May 2008 governing sediment management states that: 'sediments not returned to water bodies must be subject, as a priority, under acceptable technical and economic conditions, to appropriate treatment allowing them to be used as aggregates. Therefore, non-submersible but non-hazardous sediments can potentially be recovered for road engineering, provided that they comply with the technical specifications in force.

3.1 Sediment integration in road structure

3.1.1. Description of a typical road structure

Roads are composed of a superposition of layers (Figure 3) with distinct mechanical characteristics. In a pavement structure, there are three main layers: (A) the subgrade, (BC) the foundation layers (subbase and base course) and (D) the surface layer (surface course or wearing course and linking material).



A.) Subgrade B.) Subbase C.) Base course D.) Paver base (may be paved or covered by asphalt)

Figure 3. Typical cross-section of a road structure (https://en.wikipedia.org/wiki/Base_course)

The embankment is generally topped by a subgrade layer. The soil-support and subgrade assembly are the support platform of the roadway (and may include a subbase). The base course has dual functions. During construction, it protects the subgrade from rain and the effects of the freeze-thaw cycle. It also facilitates levelling and machine circulation. Once in service, it makes it possible to homogenise the mechanical characteristics of the materials constituting the soil or embankment and to improve long-term bearing capacity.

The base course and the sub-base layer form the actual roadway body, which supports the loads produced by the traffic and distributes them on the support platform in order to maintain the deformations at a permissible level. The base layer, closer to the surface of the roadway, undergoes significant stresses and deformations; therefore, it must have higher mechanical support characteristics than the subgrade.

The surface layer consists of the wearing course and optionally a binding layer. It has two functions, on one hand to protect the body of roadway against water infiltration and on the other hand to directly receive the pressure of vehicle tyres and to send that towards the road structure after suffering the permissible deformation.

In the road structure, load distribution is smaller and smaller from top to bottom. This makes it possible to use materials having various mechanical characteristics according to their position in the structure of the roadway.

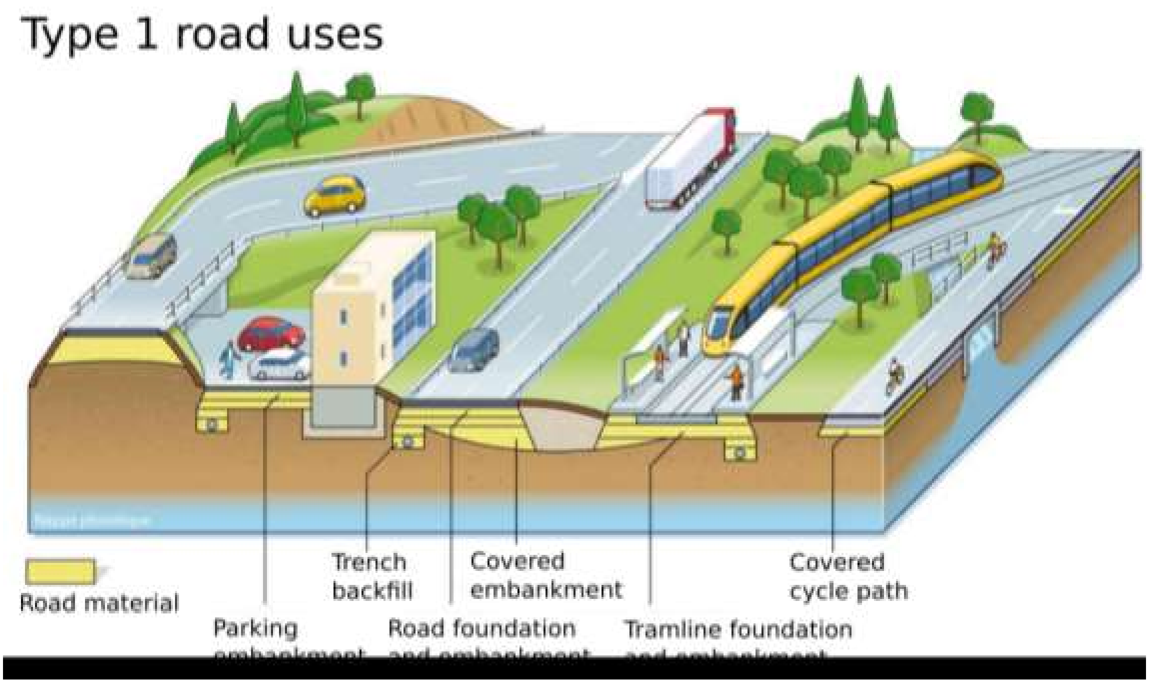
3.1.2 Possible road usages

As part of use in road engineering, dredged sediments are considered as 'alternative materials'. This term defines any material made from waste and intended to be used alone or mixed with other alternative or non-alternative minerals. An alternative material is the constituent of a road material. In accordance with the methodological guide 'Acceptability of alternative materials in road engineering' (SETRA, 2011), the road uses likely to be envisaged are as follows (FIG. 4):

- Uses in road underlays or paved shoulders (type 1 road uses): backfill under construction, subbase, base course and binding layer.
- Uses of technical backfill related to the road and shoulder infrastructure, in the case of covered uses (type 2 road use).

A road structure is deemed to be paved if its surface layer is made using asphalt, bituminous mixes, surface wear coatings, concrete, cement or pavers bonded with a bonded material and if it has a minimum slope of 1% at all points (SETRA, 2011).

A road structure is deemed to be covered if the road materials that are present are covered by at least 30 centimetres of natural materials and if it has at all points of its outer envelope a minimum slope of 5% (SETRA, 2011).



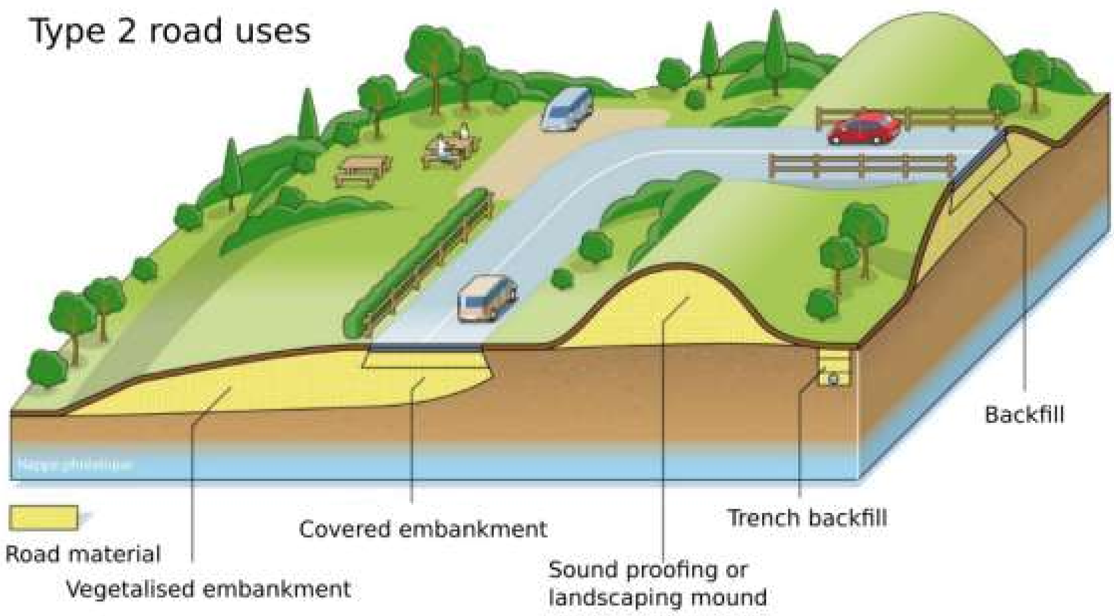


Figure 4. Illustration of 'type 1' and 'type 2' road uses (adapted from SETRA, 2011)

3.2 Existing regulations and procedures

Current regulations require at least a laboratory feasibility study to justify the use of alternative materials in road engineering. The geotechnical, mechanical and environmental aspects of this preliminary study are detailed in the paragraphs below. The flow chart incorporating regulatory recommendations is shown in Figure 5.

3.2.1 Geotechnical and mechanical aspects

The conditions of use of road construction materials are specified in the SETRA-LCPC 'Technical guide for embankments and form layers', the latest edition of which dates from July 2000. Standard NF P 11-300 (Execution of works - Classification of materials used in the construction of embankments and road surface layers) is directly derived from this guide. It is also known as the 'GTR Classification' and defines the geotechnical characteristics of natural materials and industrial by-products (including demolition waste) that can be used in backfill road infrastructure.

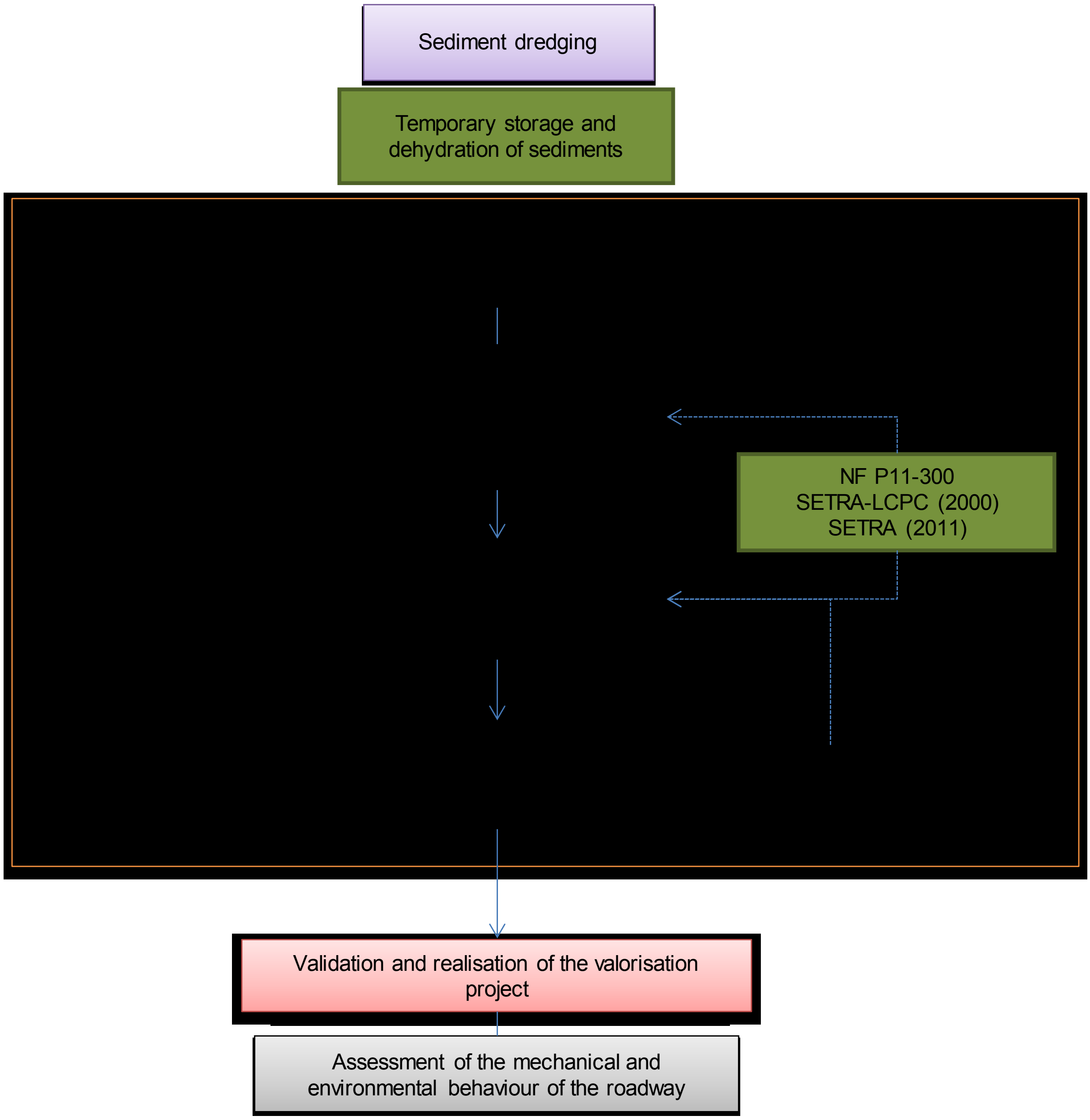


Figure 5. Dredged sediment use flow chart integrating only existing regulations and procedures in road engineering

3.2.2 Environmental aspects

Assessment of environmental acceptability

The SETRA Environmental Acceptability Guide (2011) provides an approach for how to assess the environmental acceptability of alternative materials developed from waste and intended for use in road techniques in the form of aggregates, gravels, soils, fillers and binders. The overall objective of the environmental characterisation step is to demonstrate, for the intended road use, that emissions of waste and waste-based road material are consistent with meeting the water quality objectives of the methodological guide. These materials must be characterised according to their leaching and/or percolation behaviour and according to their intrinsic pollutant content. The SETRA guide (2011) proposes three different investigation levels:

Level 1: Characterisation based on leaching tests according to standard NF EN 12457-2 and total content analysis with a variability study. The comparison of the measured concentrations with the leaching thresholds defined in the SETRA guide makes it possible to judge the environmental quality of the materials.

Level 2: Characterisation based on percolation tests (standard NF CEN/TS 14405) and leaching (standard NF EN 12457-2). To evaluate whether the percolation results comply, the SETRA guide on leaching thresholds is used.

Level 3: This level is used if the road material has non-compliant leachate results in the leaching and percolation tests. Those are generally based on a specific study to characterise how the material is altered and how pollutants in soils and groundwater are emitted (according to standard NF EN 12920 + A1). Recommendations for this last step are applicable to the design and the follow-up of experimental pads or lysimeters, with leachate collection.

The guide also specifies that any non-hazardous fraction resulting from a hazardous waste treatment operation - excluding any stabilisation operation - is considered non-hazardous waste. Waste stabilisation, dilution or mixing for the sole purpose of meeting the SETRA acceptability criteria is prohibited.

An impact study

Before implementing any road infrastructure, first the environmental and health risks associated with the use of non-submersible sediments must be assessed. This impact study has a regulatory basis (articles L.122-1 and following and R122-1 and following of the Environment code) and its content is specified in article R122-5 of the Environment code.

4. Operational methodology of the SEDIMATERIAUX approach

4.1 Existing regulations and procedures

The SEDIMATERIAUX operational methodology integrates all the existing regulations and procedures described in the previous chapter. Nevertheless, taking only these elements (Figure 6) into account is not a sufficient guarantee for technical, mechanical and environmental feasibility of the beneficial use of dredged sediments in road engineering. This is why the operational methodology of the SEDIMATERIAUX approach has defined and integrated complementary procedures. These are essential for the successful completion of projects.

Gaps were identified in existing procedures:

- The characterisation tests, defined in the guides and standards used in road engineering (NF P11-300, SETRA-LCPC, 2000, SETRA, 2011) are insufficient in terms of analyses, to evaluate the technical feasibility of the beneficial use of dredged sediments in road engineering.

- The transition between the 'preliminary laboratory study' and 'use project' phases is too quick. The absence of intermediate feasibility studies between these two phases represents a significant risk for the developer, who has to guarantee the environmental safety of the sediment use project.

- Specific environmental monitoring protocols of facilities used during the 'assessment of the mechanical behaviour of the roadway' phase are lacking.

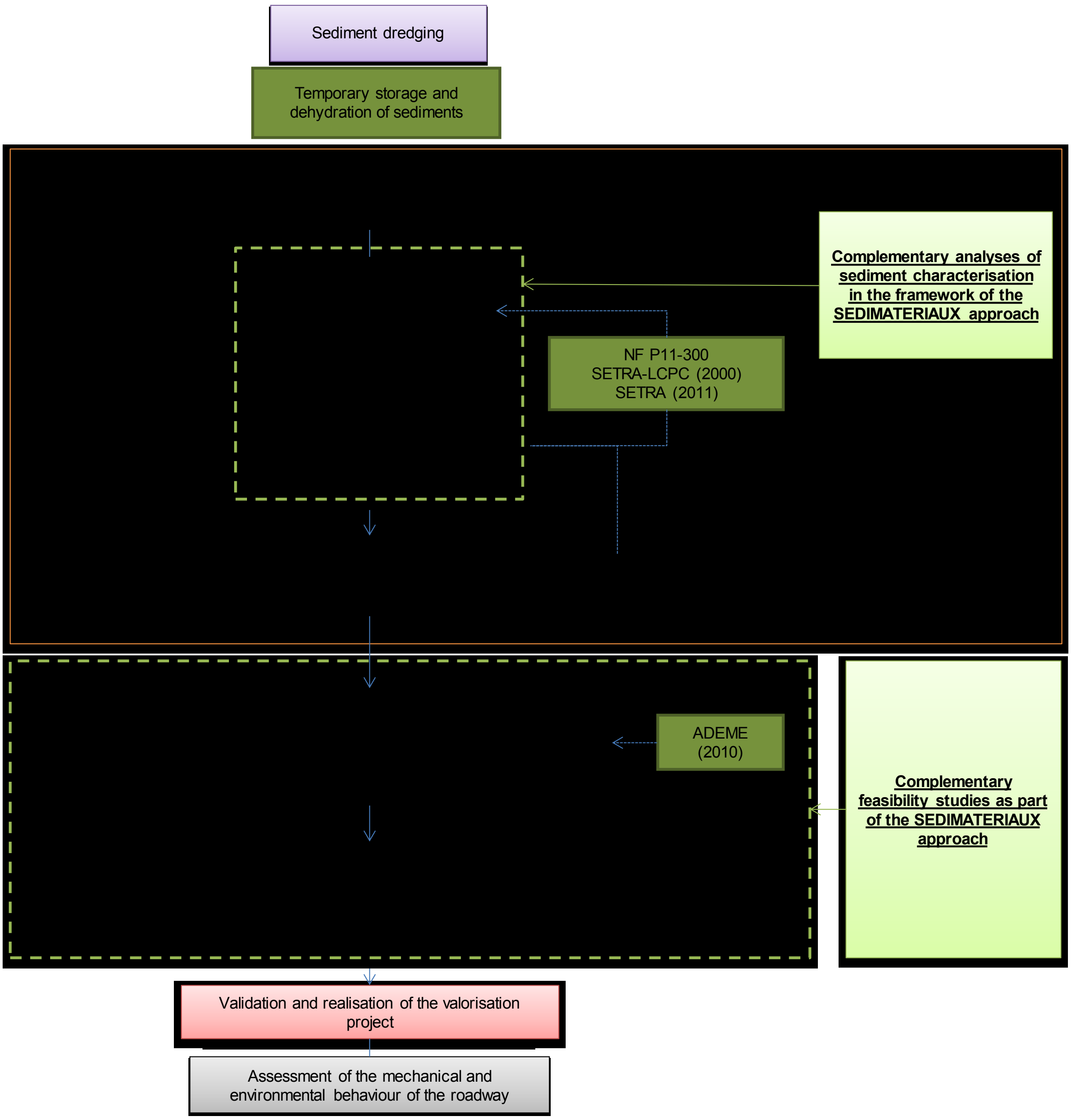


Figure 6. Dredged sediment use flow chart integrating existing procedures and complements to the SEDIMATERIAUX methodology.

Note: The SEDIMATERIAUX approach does not supersede any regulatory obligations of project owners while they are carrying out their sediment projects.

4.2 A three-phase methodology

The experimental methodology used in the framework of the SEDIMATERIAUX approach requires, as a matter of principle, taking more precautions than the current standards and to complement existing procedures (see following chapters), in particular to acquire data that is not yet available and then allow operators to use sediments that meet the criteria validated under this methodology.
This methodology was developed by the Ecole des Mines de Douai as part of the SEDIMATERIAUX approach and relies on feedback from projects carried out at Dunkirk's 'Grand Port Maritime'. This is applicable to any type of sediment. There are three cumulative and dependent phases (Figure 7):

- PHASE 1: CHARACTERISATION (Duration: 3 to 4 months)
- PHASE 2: LABORATORY (9 to 12 months)
- PHASE 3: FIELD (12 months minimum)

These three phases are described is what follows. In summary, in phase 1 the sediments' specifications are determined after dredging and potential uses according to those physical, chemical, mechanical and environmental characteristics are identified. The second phase of the methodology investigates the technical feasibility of upgrading dredged sediment in the various applications envisaged at the laboratory scale. In phase 3, an instrumented field test (a pilot of about ten meters or a significant project) is carried out and monitored for one year to validate the applications tested in the laboratory. Validation of this last phase would confirm that this sediment could be used as intended in a given environmental context.

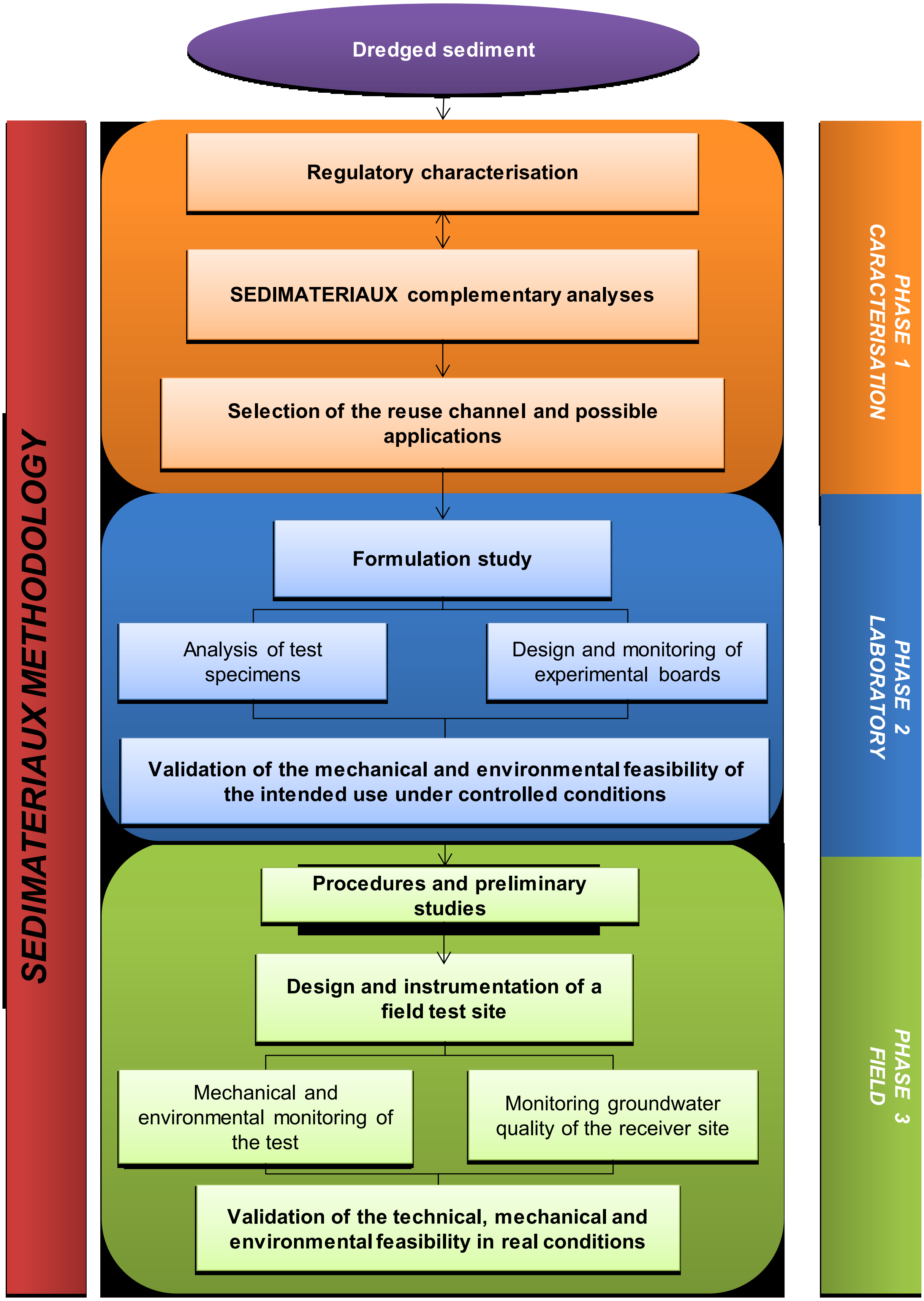


Figure 7. Description of the methodology developed as part of the SEDIMATERIAUX approach

5. Phase 1: Characterisation of dredged sediment

5.1 Objective

The characterisation phase identifies deposits of potentially valuable sediments and increases understanding of their physical, geotechnical, mineralogical, mechanical, chemical and environmental properties. The purpose of this phase is to identify potential use channels based on sediment characteristics and the operator's needs.
In addition, the technical and environmental recommendations (perimeter to be instrumented, installation of a geo-membrane, sediment pollutants treatment, etc.) issued at the end of this phase will help better define the feasibility studies to be performed in the laboratory and in the field.

5.2 Regulatory Characterisation

Methods for on-land management of dredged sediments and the selection of use channels depend mainly on how big, how hazardous and how radioactive the deposits are. An accurate identification of the nature of the sediments to be dredged is based on the implementation of a sampling plan adapted to the specificities of the study site. This sampling strategy will be established in accordance with existing regulatory or technical standards such as the VNF technical circular on dredging operations or the circular of 14 June 2000. The purpose of the sampling plan is to obtain samples representative of the area to be dredged for the regulatory analyses.
This preliminary characterisation, under the Waste Framework Directive No. 2008/98/CE of 19/11/2008 and the Public Health Code (Article R.1333-2 of the Public Health Code), will allow the operator to define the on-land management of its dredged sediments through additional tests (Figure 8). So, non-hazardous sediment deposits (heading 17 05 06: inert and non-inert sediments) may be the subject of a feasibility study for use on land, while sediment deposits identified as hazardous and/or containing radioactive substances will have to be treated before disposal or, where appropriate, beneficial use.

5.2.1 Hazard analysis

Waste Framework Directive no. 2008/98/CE of 19/11/2008 (transposed into French law in the Environmental Code, in particular in articles R541-8 and its annexes and R541-10) classifies dredged sediments under two headings:

- heading 17 05 05*: dredged sludge containing dangerous substances
- heading 17 05 06: dredged sludge other than those mentioned in 17 05 05 *

The asterisk following the code 17 05 05 indicates that it is hazardous waste. To define the management methods for dredged sludge, it is therefore necessary to identify whether sediments fall into the 17 05 05* or 17 05 06 category, whatever the management system envisaged (ultimate storage or for valuation).
Thus, dredged sediments are classified as hazardous based on the assessment of the hazard properties defined by the Environmental Code (Table 2) if it meets the criteria for attributing one or more hazard properties.

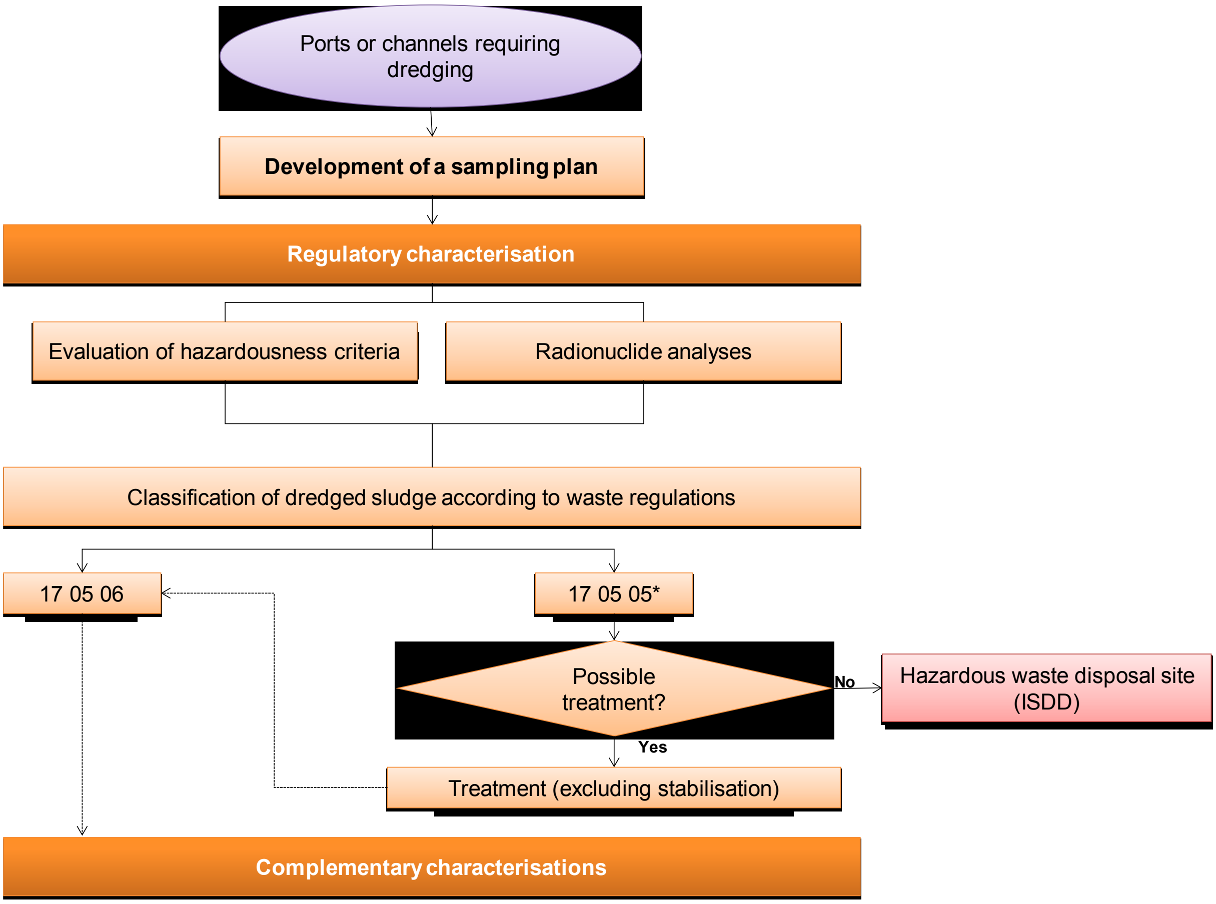


Figure 8. Regulatory characterisation of dredged sediments for use on land

Waste is classified as non-hazardous if:

- it does not meet the criteria for the assignment of any hazard properties for which the assessment method is currently defined in the Environmental Code (i.e. H1 to H8, H10 and H11) and
- if studying properties H9, H12, H13, H14 and H15 demonstrates the non-dangerous nature of the waste for these properties.

Table 2. Hazard criteria to be taken into account when assessing the danger of sediment.

Criteria	Definition
H1 Explosive	substances and preparations which may explode under the effect of flame or which are more sensitive to shocks or friction than dinitrobenzene.
H2 Oxidising	substances and preparations which exhibit highly exothermic reactions when in contact with other substances, particularly flammable substances.
H3-A **Highly Flammable**	— liquid substances and preparations having a flash point below 21 °C (including extremely flammable liquids), or — substances and preparations which may become hot and finally catch fire in contact with air at ambient temperature without any application of energy, or — solid substances and preparations which may readily catch fire after brief contact with a source of ignition and which continue to burn or to be consumed after removal of the source of ignition, or — gaseous substances and preparations which are flammable in air at normal pressure, or — substances and preparations which, in contact with water or damp air, evolve highly flammable gases in dangerous quantities.
H3-B Flammable	liquid substances and preparations having a flash point equal to or greater than 21 °C and less than or equal to 55°C.
H4 Irritant	non-corrosive substances and preparations which, through immediate, prolonged or repeated contact with the skin or mucous membrane, can cause inflammation.
H5 Harmful	substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may involve limited health risks.
H6 Toxic	substances and preparations (including very toxic substances and preparations) which, if they are inhaled or ingested or if they penetrate the skin, may involve serious, acute or chronic health risks and even death.
H7 Carcinogenic	substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce cancer or increase its incidence.
H8 Corrosive	substances and preparations which may destroy living tissue on contact.
H9 Infectious	substances and preparations containing viable micro-organisms or their toxins which are known or reliably believed to cause disease in man or other living organisms.
H10 Toxic for reproduction	substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce non-hereditary congenital malformations or increase their incidence.
H11 Mutagenic	substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce hereditary genetic defects or increase their incidence.
H12	Waste which releases toxic or very toxic gases in contact with water, air or an acid.
H13 Sensitising	substances and preparations which, if they are inhaled or if they penetrate the skin, are capable of eliciting a reaction of hypersensitisation such that on further exposure to the substance or preparation, characteristic adverse effects are produced.
H14 Ecotoxic	waste which presents or may present immediate or delayed risks for one or more sectors of the environment.
H15	Waste capable by any means, after disposal, of yielding another substance, e.g. a leachate, which possesses any of the characteristics listed above

Properties not relevant for dredged sediments: H1, H2 and H3

The Order of 08 July 2003 gives the criteria and methods for evaluating the hazard properties H1, H2 and H3. Given the nature of the dredged sediments, it is not necessary to characterise how hazardous the materials are according to these properties:

H1 explosive: sediments by their nature and origin do not contain certain groups of reagents such as nitro components, diazonium salts and peroxyl in the structural formula, meaning that the waste is not likely to decompose rapidly with release of gases or heat (i.e. that this material presents no explosion risk).

H2 Oxidising: In the proposed assessment methods, the reference substances are gases, liquids (nitric acid and cellulose mixture) and solids (potassium bromate/cellulose mixture). The sediments in place are not of a nature to contain a mixture of potassium bromate/cellulose.

H3 Flammable: Sediments are not likely to contain pyrophoric materials, i.e. materials that can ignite on contact with air, water or pressure. Port, river and canal sediments are already in contact with water.

It is therefore not necessary to carry out the H1, H2 and H3 tests.

Evaluation of properties H4, H5, H6, H7, H8, H10 and H11

The evaluation of the hazard properties H4 to H8, H10 and H11 is based on the knowledge of the chemical composition of the waste and the calculation rules defined by the Environmental Code. The process of assessing how hazardous the waste is based on its chemical composition has four stages:
1) Conducting laboratory tests for organic and inorganic substances that may be present in the waste. In the case of sediments, the list of substances sought will be established based on the regulations on the law on water and waste. Where appropriate, other chemicals may be analysed according to local issues.
2) The speciation of metals as mineral substances;
3) The search for the hazard properties of the substances identified in the sediment;
4) The application of the classification rules.
For the details of the different stages of this process, the project owner should consult the technical document 'Guide for the classification of waste according to their dangerousness according to the Environmental Code and the SEVESO II regulation' (INERIS, 2013).

Evaluation of property H14

The H14 property assessment currently has no method with regulatory status. However, there is a battery of tests for sediments (freshwater and seawater) that has been proposed by the ministerial working group 'Sediment Hazard', as a staged approach (Figure 9). The protocol includes a preliminary centrifugation phase to eliminate chlorides that are likely to cause a toxic effect in terrestrial organisms. The protocol comprises then acute ecotoxicity and chronic ecotoxicity tests from leachates and then acute ecotoxicity tests against terrestrial organisms (higher plants seeds) on the raw matrix after centrifugation. When any test demonstrates the ecotoxic nature of the waste, it may be declared dangerous and the tests may be stopped. If not, the complete battery of bioassays must be carried out.
The ‘Sediment Hazard Level' working group recommends the implementation of the H14 protocol only for all sediment samples which chemical analyses on the <2 mm fraction exceed one of the regulatory thresholds of

level S1 of the decree of August 9, 2006 (Table 3). The threshold value in total PCBs corresponds to the sum of the concentrations of the seven indicator PCBs: PCBs 28, 52, 101, 118, 138, 153 and 180. The threshold value of the total PAH parameter corresponds to the sum of the concentrations of the following 16 PAHs: naphthalene, acenaphthylene, fluorene, acenaphthene, anthracene, phenanthrene, fluoranthene, pyrene, benzo[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[a]pyrene, indeno-pyrene, dibenzo[a]anthracene, benzo[ghi]perylene.

Table 3. Thresholds S1 from the decree of August 9, 2006

Parameter	Level S1 (mg/kg)
As	30
Cd	2
Cu	150
Total Cr	100
Hg	1
Ni	50
Pb	100
Zn	300
total PCBs	0.680
total PAHs*	22.8

**16 PAHs from the EPA list: naphthalene, acenaphthylene, fluorene, acenaphthene, anthracene, phenanthrene, fluoranthene, pyrene, benzo[a]anthracene, chrysene, benzo[b]fluoranthene, benzo[a]pyrene, indeno-pyrene, dibenzo[a]anthracene, benzo[ghi]perylene.*

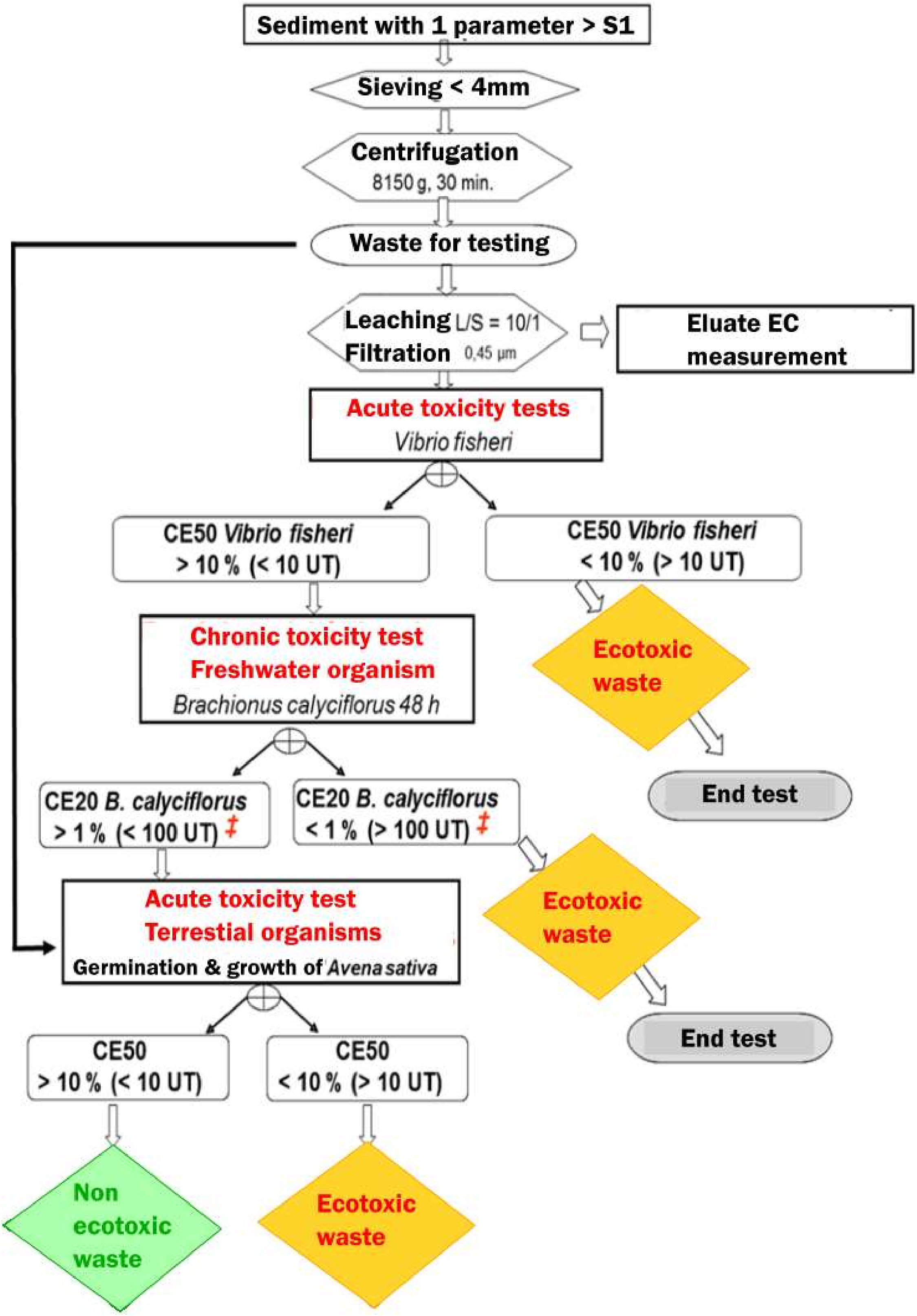


Figure 9. Protocol for assessing the H14 hazard property for marine and river sediments

Properties without any evaluation method defined in the environmental code: H9, H12, H13 and H15

These properties do not currently have a recognised evaluation method, either at the regulatory level, or defined by consensus of experts in the field. For some of them, work is under way to establish evaluation methods and criteria. In 2013 INERIS proposed a 'Guide to the classification of waste according to their hazard level according to the Environment Code and the SEVESO II regulation', elements to aid in evaluating these properties, which must not be excluded from the file.

5.2.2 Radioactivity analysis

Some sediment can present specific contamination problems requiring the realisation of radio-ecological analyses. For the purposes of Council Directive 96/26/Euratom of 13/05/96, a radioactive substance means any substance that contains one or more radionuclides whose activity or concentration cannot be neglected from the point of view of radiation protection.
In addition, the Public Health Code prohibits the addition of radionuclides in construction products (R.1333-2 of the Public Health Code). Project owners wishing to upgrade their deposits of sediments in terrestrial works must therefore ensure the absence of radioactive substances. In dredged sediments radioactivity is analysed according to ISO 18589.

5.3 Complementary characterisations

The characterisation study provides additional information on the physical, geotechnical, mechanical and environmental properties of sediment deposits (Figure 10). The methods of on-land management of dredged sediments and the selection of the use chain depend essentially on this complementary study. The latter concerns only deposits of potentially valuable sediments on land.

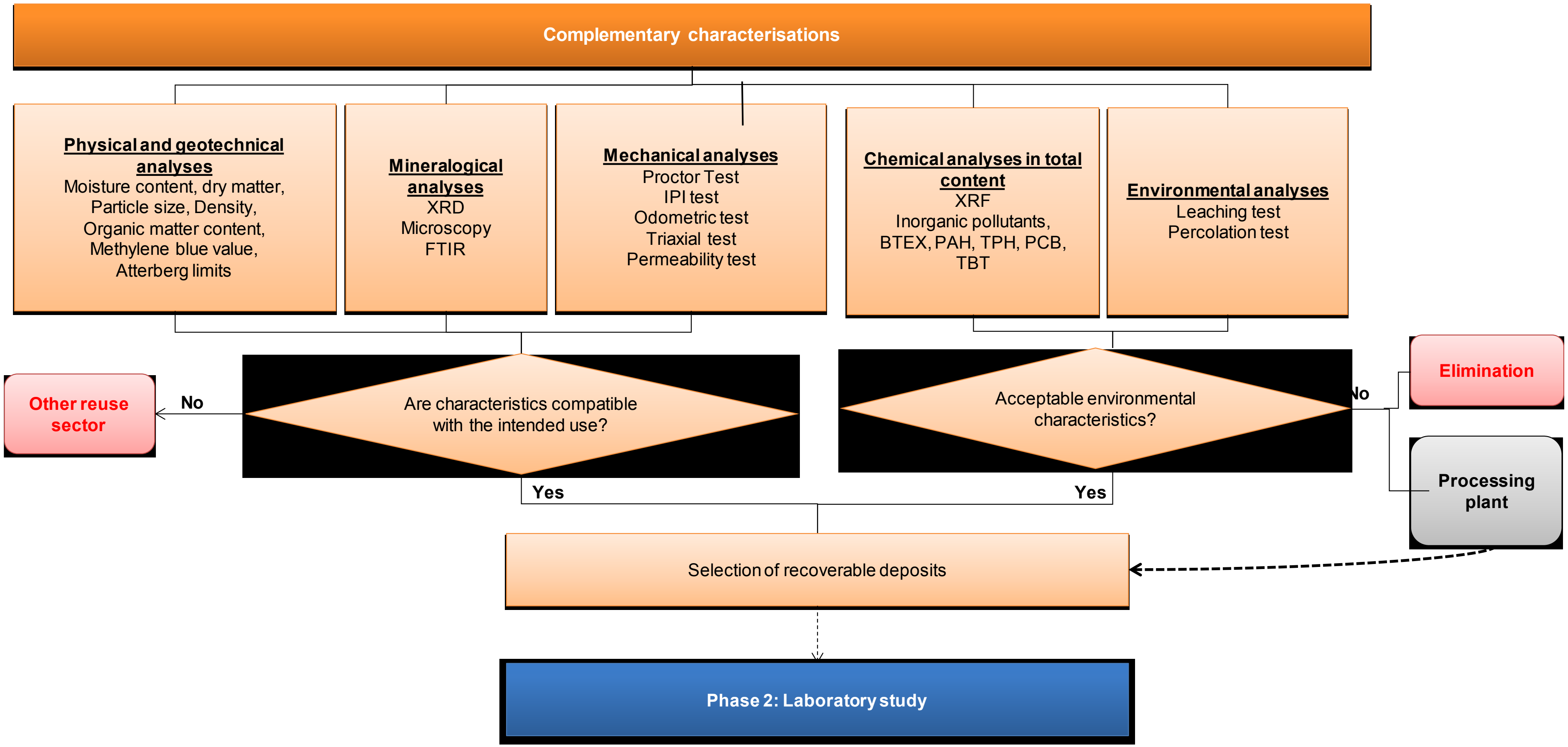


Figure 10. Additional characterisations on raw sediments

5.3.1 Physical and geotechnical analyses

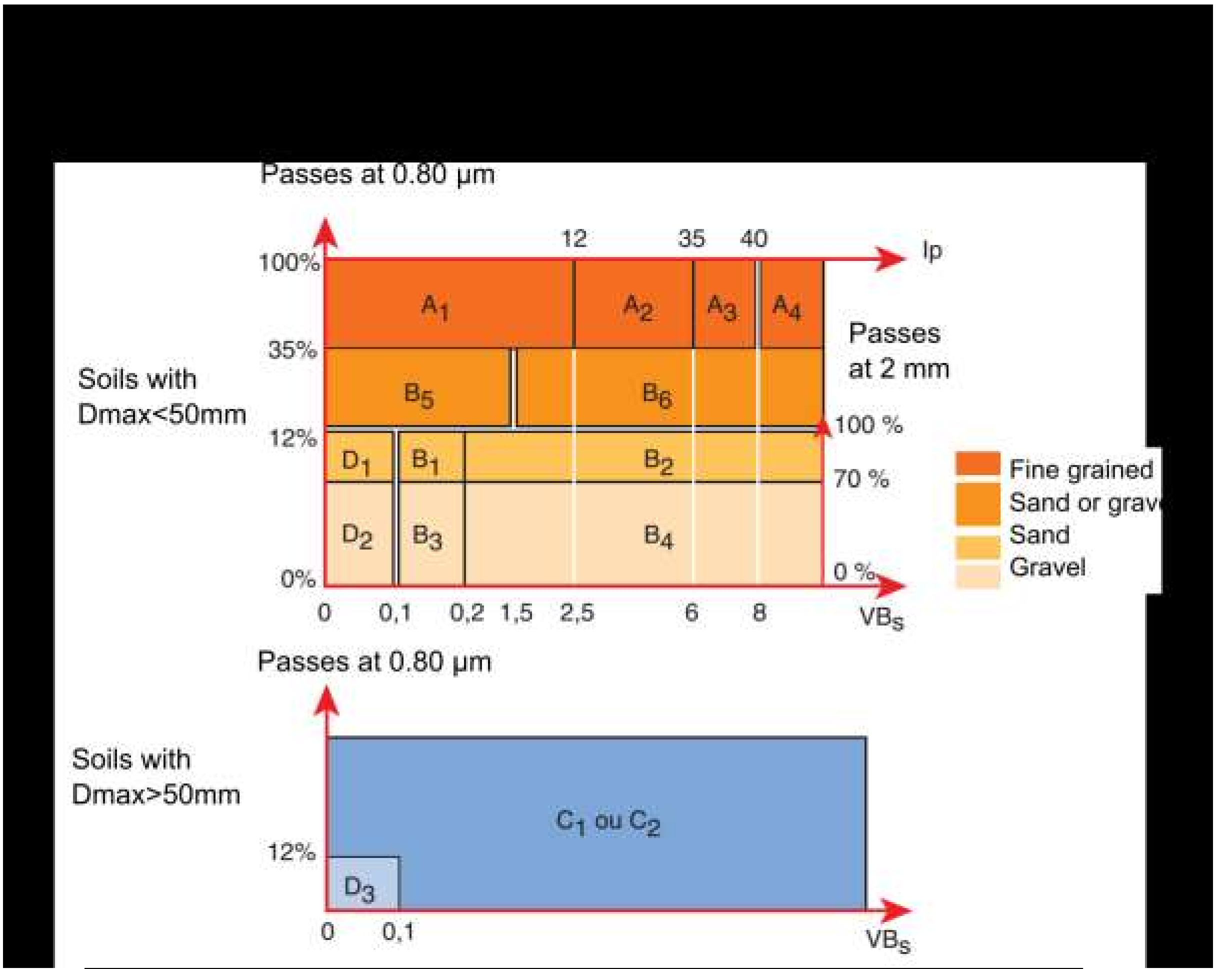
The physical and geotechnical characterisation of sediments provides essential information on the nature of sediments and how they will behave when used. The circular of 14 June 2000 specifies the general instructions for sampling and analysis of sediments. Apart from the quantity of materials to be dredged, other analyses include determination of the dry matter and water contents, the grain size distribution (% sand, silt, clay), the absolute density and the organic material content. These analyses should be complemented by other geotechnical analytical features such as methylene blue value and Atterberg limits. The table below summarises the various physical and geotechnical analyses and their associated standards.

Table 4. Physical and geotechnical analyses on raw sediments

Test	Standards
Dry matter	EN 14346
Water content	NF P94-050
Grain size analysis	ISO 13 320-1, NF P94-057, NF P94-040
Absolute density	NF P94-054, XP CEN ISO/TS 17892-3
Organic matter	EN 15169, NF XP P94-047
Methylene blue test	NF P94-068
Atterberg limits: **Liquid limit with Casagrande cup** **Roll plastic limit**	NF P94-051
Atterberg limits: **Liquid limit with cone penetrometer**	NF P94-052-1

The SETRA-LCPC technical guide (2000) provides a precise classification of a wide variety of materials (Figure 11). The guide proposes suitable treatment techniques according to the material's specificities. With a particle size of less than 50 mm and a significant clay fraction, dredged sediments generally have similar geotechnical properties to class A soils. Depending on the value of the organic matter content of the harbour sediments, they can also fall under class F.

Because of their physical characteristics, dredged sediments generally belong to the class of clay-silt materials with varying levels of organic matter. This type of material is difficult to use in road construction because of its sensitivity to water and compressibility. In addition, the raw sediments have a low immediate bearing index. To increase the mechanical performance of sediments, an addition of granular correctors followed by treatment with hydraulic binders and/or aerial (cement and/or lime) is generally used.



Minerals and rock material	Sedimentary rocks	Carbonate rocks	Chalk	R1
			Limestone	R2
		Argillaceous rocks	Marl, claystone, pelite	R3
		Siliceous rocks	Sandstone, pudding stone, breccia	R4
		Saline rocks	Salt, gypsum	R5
	Magmatic and metamorphic rocks	Granite, basalt, andesite, gneiss, schist, slate		R6
Specific material	Organic soils and industrial byproducts			F

Figure 11. Synoptic classification of materials according to their nature, according to standard NF P 11-300 (CIMBETON, 2009)

5.3.2 Mineralogical analyses

Mineralogical analysis is important because it provides better understanding of the sedimentary matrix and detects the principal mineralogical phases (amorphous or crystallised) in the sediments (Figure 12). Mineralogical characterisation of the sediments includes X-ray fluorescence analysis of the major elements (Standard NF EN 15309) and the detection of the mineralogical phases by X-ray diffraction (XRD). Microscopic techniques (optical or electronic) can also be used to complete the structural analysis of sediments, in particular by researching the nature of amorphous phases.

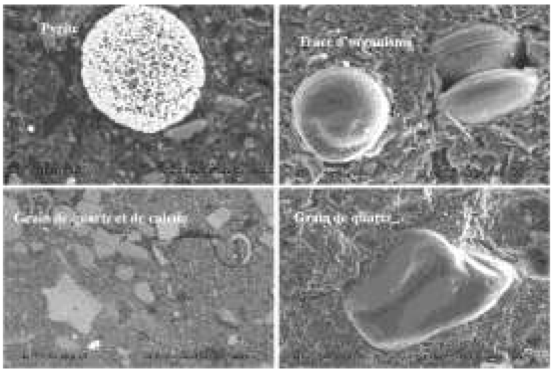


Figure 12. Scanning electron microscopy (SEM) photomicrographs of a marine sediment (trace d'organisme = organism image, Grain de quarts = quarts grain)

5.3.3 Mechanical analyses

The use of sediments in road layers must meet minimum support requirements. To achieve this, the mechanical characterisation of the raw sediments is carried out according to the SETRA-LCPC Technical Guide (2000). This step is decisive for carrying out the formulation study of the road material.

Proctor test

The final bulk density of a compacted soil depends on the nature of the soil, the moisture content and the compaction energy. The compacting makes it possible to tighten the texture of the ground, to reduce its deformations, to improve its bearing capacity and its resistance. For a given soil and for a specific compaction mode, there is a single water content corresponding to the maximum density.

For a base layer, the optimal water content and the corresponding density are determined by the Proctor test according to standard NF P 94-093.

Immediate Bearing Index (IBI)

This test is carried out according to standard NF P 94-078 to determine the lift of the material. The IBI, which describes the ability of the material to withstand the loads generated by construction machinery during work, is defined by the ratio between the force measured for the depression of a cylindrical rod in the test material and the given force compared to a reference material.

5.3.4 Chemical analyses

The management of dredged sediments is governed by the Water Act No. 92.3 of 3 January 1992 and the decrees adopted for its application. The reference thresholds to be taken into account during a port sediment analysis are defined by the decrees of 9 August 2006 (Trace elements and PCBs), 23 December 2009 (TBT) and 08 February 2013 for polycyclic aromatic hydrocarbons (PAH) (Tables 5 and 6). The thresholds defined in these decrees (N1 and N2) characterise the chemical quality of the material and help to determine, if necessary, the approach to adopt for studies and technical solutions. These quality thresholds are also benchmarks for directing sediments towards a management system: land-based management for use or final storage/containment. Some sites may have specific contamination issues that may require analysis of regulated pollutants under the Water Act. The preliminary study of the site during the zoning stage will, through existing documents, identify all the contaminants likely to be present in the sediments.

Table 5. Reference levels of the Decree of August 9, 2006

Pollutants (mg/kg*)	Level 1	Level 2
Arsenic (As)	25	50
Cadmium (Cd)	1.2	2.4
Chromium (Cr)	90	180
Copper (Cu)	45	90
Mercury (Hg)	0.4	0.8
Nickel (Ni)	37	74
Lead (Pb)	100	200
Zinc (Zn)	276	552
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
Total PCB	0.5	1

* on dry sediment analysed on fraction < 2 mm

Table 6. Reference levels of the Decrees of 23 December 2009 (TBT) and 08 February 2013 (PAH)

Pollutants (µg/kg)	Level 1	Level 2
Tributyltin (TBT)	100	400
Naphthalene	160	1130
Acenaphthene	15	260
Acenaphthylene	40	340
Fluorene	20	280
Anthracene	85	590
Phenanthrene	240	870
Fluoranthene	600	2850
Pyrene	500	1500
Benzo[a]anthracene	260	930
Chrysene	380	1590
Benzo[b]fluoranthene	400	900
Benzo[k]fluoranthene	200	400
Benzo[a]pyrene	430	1015
Dibenzo[a,h]anthracene	60	160
Benzo[g,h,i]perylene	1700	5650
Indeno[1,2,3-cd]pyrene	1700	5650

5.3.5 Environmental analyses

In the absence of a specific methodological framework for the use of dredged sediments in road engineering, the environmental characterisation has to be done using standardised tests based on the existing regulatory and technical references, namely the guide 'Acceptability of alternative materials in road engineering' (SETRA, 2011). This repository makes it possible to identify the possibilities for recovering hazardous or non-inert materials on the basis of total content, leaching and percolation thresholds.

SETRA framework (2011)

Thus, dredged sediments must be characterised according to their leaching behaviour (standard NF EN 12457-2), percolation (standard NF CEN/TS 14405) and according to their intrinsic content of pollutants by homogeneous deposit (Tables 7, 8, 9 and 10). The substances measured for total content are those in the Decree of 12/12/14 relating to inert waste storage facilities (Table 8).

For type 1 and 2 uses, the limit leaching values proposed by the SETRA guide are between those of the Decree of 12/12/14 (Table 7) and the compliance thresholds of Decision 2003/33/EC for the admission of non-hazardous waste to a storage facility (Table 9). If the measured values comply with the leaching thresholds in Table 7 and the total content thresholds in Table 8, the waste is classified as an alternative material and its use is possible for Type 1 and Type 2 road use (see Figure 4).

For waste not complying with the leaching thresholds in Table 7, the SETRA Guide (2011) proposes specific leaching and/or percolation thresholds for certain applications. The guide therefore makes it possible to develop non-inert and non-hazardous waste deposits for very specific applications.

For type 1 uses, the guide proposes the use of leaching thresholds similar to the compliance thresholds of Decision 2003/33/EC for the admission of non-hazardous waste to a storage facility (Table 9). Coated pavement or shoulder pavement applications, covered technical backfill or shoulder are possible for waste complying with the proposed percolation thresholds (Table 10).

Table 7. Limit leaching test values required to justify all the uses covered by the Acceptability Guide for Alternative Materials in Road Technology (SETRA, 2011)

Parameters	Cumulative released amount at L/S = 10 l/kg (leaching test NF EN 12457-2 or NF EN 12457-4)		
	Value to be met by at least 80% of the samples (mg/kg of dry matter)	Value to be met by at least 95% of the samples (mg/kg of dry matter)	Value to be met by 100% of the samples (mg/kg of dry material)
As	0.5	1	1.5
Ba	20	40	60
Cd	0.04	0.08	0.12
Total Cr	0.5	1	1.5
Cu	2	4	6
Hg	0.01	0.02	0.03
Mo	0.5	1	1.5
Ni	0.4	0.8	1.2
Pb	0.5	1	1.5
Sb	0.06	0.12	0.18
Se	0.1	0.2	0.3
Zn	4	8	12
Fluoride	10	20	30
Chloride (*)	800	1600	2400
Sulfate (*)	1000	2000	3000
Soluble fraction (*)	4000	8000	12000
pH	[5.5-12.5]	[5.5-12.8]	[5.5-13.0]

(*) Concerning chloride, sulfate and the soluble fraction, for compliance, either the values associated with chlorides and sulfates, or values associated with the soluble fraction must be respected.

Table 8. Limit values not to be exceeded in total content to be acceptable for use in road engineering

Parameter	Threshold to be satisfied by at least 80% of samples (mg/kg on dry matter)	Threshold to be satisfied by 100% of samples (mg/kg on dry matter)
TOC (*)	3000	6000
BTEX (Benzene, toluene, ethylbenzene and xylenes)	6	
PCB (Polychlorobiphenyls, 7 congeners) **Congeners no. 28, 52, 101, 118, 138, 153 and 183**	1	
THC (total hydrocarbons, C10 to C40) (*)	500	
PAH (Polycyclic Aromatic Hydrocarbons) (*)	50	

(*) For road structure use (subbase or subgrade layer) or for surface layers (wearing course or binding layer), the limit values associated with total organic carbon (TOC), total hydrocarbons (HCT) and hydrocarbons Polycyclic aromatic hydrocarbons (PAHs) can be adapted, in particular to take into account the contribution of bituminous binders (TOC and HCT) or the implementation technique (PAH). Any modification of the limit value must be validated by the Ministry of the Environment, in particular while in the development of an application guide.

Table 9. Leaching thresholds not to be exceeded for use in road engineering (SETRA, 2011)

Parameters	Cumulated release under L/S = 10 l/kg (leaching test under NF EN 12457-2 or NF EN 12457-4)
	Value (mg/kg on dry matter)
As	2
Ba	100
Cd	1
Total Cr	10
Cu	50
Hg	0.2
Mo	10
Ni	10
Pb	10
Sb	0.7
Se	0.5
Zn	50
Fluoride	150
Chloride (*)	15000
Sulfate (*)	20000
Soluble fraction (*)	60000
(*) For chloride, sulfate and the soluble fraction to comply, either total chlorides and sulfates or the values associated with the soluble fraction must be respected.	

Table 10. Limits in percolation required to justify the use of an alternative material for pavement or paved shoulder and for covered technical embankment or shoulder.

	'Subgrade or coated roadside' scenario	'Technical backfill or covered roadside' scenario
	Cumulated release under L/S = 10 l/kg (percolation test NF CEN/TS 14405)	
Parameters	Value (mg/kg on dry matter)	Value (mg/kg on dry matter)
As	0.8	0.5
Ba	56	28
Cd	0.32	0.16
Total Cr	4	2
Cu	50	50
Hg	0.08	0.04
Mo	5.6	2.8
Ni	1.6	0.8
Pb	0.8	0.5
Sb	0.4	0.2
Se	0.5	0.4
Zn	50	50
Fluoride	60	30
Chloride (*)	10000	5000
Sulfate (*)	10000	5000
pH	[5.5-12.5] to be achieved by at least 5/7 of percolates [5.5-12.8] to be achieved by at least 6/7 of percolates [5.5-13.0] to be achieved by all 7 percolates	

6. Phase 2: Laboratory study

6.1 Objective

The laboratory study phase consists of (i) developing a material that is mechanically and environmentally suitable for the intended use and (ii) studying the mechanical and environmental behaviour of the material under controlled conditions. Thus, experimental boards can be implemented to study the behaviour of the material on a given time-scale under the conditions of the scenario. This study will identify the parameters likely to influence the mechanical performance of the material in the long term as well as the potential impact of its use on the environment.

6.2 Sampling at the storage or disposal site

The objective of the sampling is to give each element present in the sediment deposit the same probability of being in the sample as it has in the initial batch. The sampling strategy will have to take into account the spatial and temporal dimensions by taking all the grain size classes randomly, by multiplying the samples and by taking into account the geometry of the pile and its mode of constitution. Standards and technical reports related to sampling provide recommended requirements. The SETRA guide (2011) gives a list of the main methods used to carry out sampling plans.

6.3 Formulation study

6.3.1 Development of road material

Composition of road material

The purpose of the formulation study is to examine the possibility of replacing a fraction of sand used in road materials with dredged sediments. Because of its availability in the harbour, the use of dredged sand in the formulation of fine sediment-based road materials presents an interesting economic solution for improving the mechanical characteristics of dredged materials. The mixture of sediment and dredged sand must then be treated with quicklime and hydraulic binder.

Concerning the composition and the percentages used in the formulation of the road materials, it is recommended to rely on the thesis works carried out in recent years at the Mines school of Douai (Dubois, 2006, Tran, 2008, Achour, 2013). In the case of use in road sub-layers, the proportions used are generally 1/3 of fine sediment and 2/3 of dredged sand. The amount of hydraulic binder is set at 6%, which is typically used for road construction treatment and the proportion of lime to be added is determined by the limiting binding test (Tremblay, 1998).

Granular Correctors

The choice of granular correctors must meet economic, technical and environmental constraints. The work of Dubois (2006) has shown that mixtures combining sand and fine sediments for dredging, among others, meet the mechanical requirements necessary for use in underlayments. The proposed methodology for selecting and adding the granular corrector is mainly based on the following parameters:

- Limiting the proportion of the fine fraction in the mixtures.
- Limiting the quantity of organic matter.
- Optimising the quantity of fine sediments.
- Optimising the particle size distribution.

Optimising the particle size distribution is a particularly important step in constituting the granular skeleton of the road material. A grain size curve can be characterised by the calculation of uniformity (Cu) and curvature

(Cc) coefficients. The Cu coefficient tells us whether the grain size distribution is narrow (Cu <2) or broad (Cu> 2).

From the additional coefficient Cc (in addition to Cu) we can determine whether the particle size is well (1 <Cc <3) or poorly graduated (Cc <1 or Cc> 3). These coefficients can be calculated using characteristic values of opening of the sieve allowing x% of the weight of the grains (D10, D30, D60) to pass (Achour, 2013)

Figure 13 presents examples of particle size distribution curves for potential constituents of a road material (30% fine sediment, 70% dredged sand, 6% hydraulic binder and 1% lime). With respective Cc and Cu coefficients of 1.8 and 6, the mixture's particle size distribution meets the uniformity and curvature criteria.

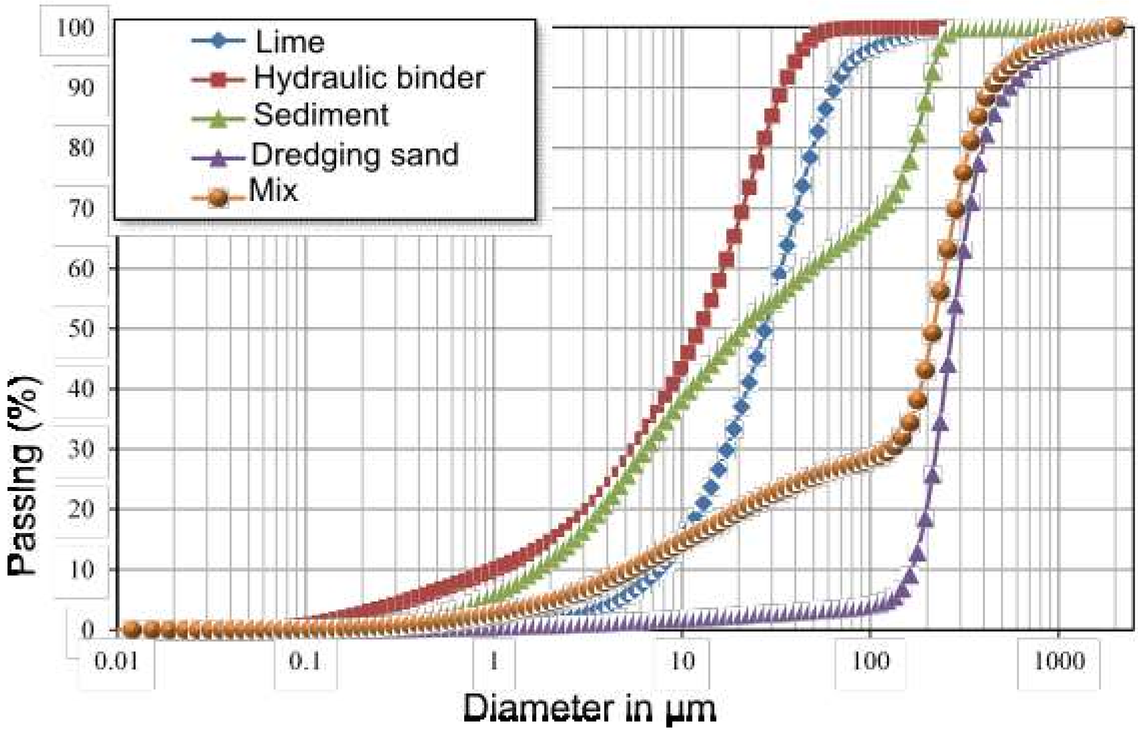


Figure 13. Particle size distribution of constituents of a road material

In terms of environmental impacts, the safety of the sands used must be verified through leaching and/or percolation tests (see previous chapter). The results of the tests are compared to the leaching thresholds of the SETRA Methodological Guide (2011) for the acceptability of alternative materials in road engineering.

Hydraulic binders

The hydraulic binder is an important constituent in the treatment of materials for use in road engineering. Its ability to agglomerate aggregates gives the material a permanent cohesion whose importance depends on the nature of the treated material, the type of binder, the amount introduced, the compactness achieved during implementation, the temperature of the medium and the age of the mixture.

The hydraulic binder sediment treatment technique is particularly suitable for the development of a road material. This technique consists of upgrading the harbour sediments in place by incorporating the binder and mixing until a homogeneous material is obtained. The hydraulic binder is a mixture with variable proportions of hydraulic elements such as clinker, blast furnace slags, pozzolanic elements and calcareous fillers.

Lime

Quicklime is generally used in stabilisation treatments but can also be used as an additive to hydraulic binders. In the treatment of fine sediments, lime reduces the water content of the treated products but also produces lime hydroxide for the activation pozzolans possibly added or may be present in the material treat. The lime content is determined by the limit fixation test, the test consists in determining the pH of a sediment suspension at a liquid/solid ratio (L/S) of 5 in the presence of a growing percentage of lime. live up to constant pH. For example, in the case of harbour sediments, lime addition at 1% results in a constant pH (Figure 14).

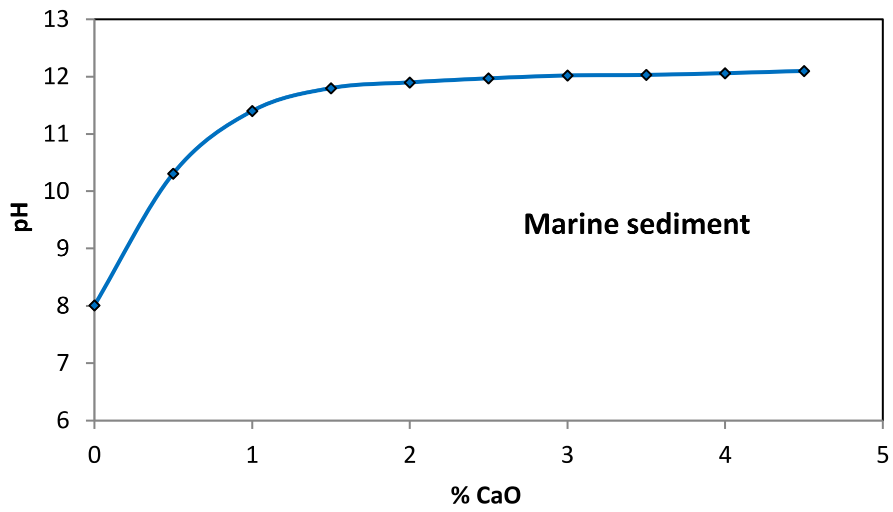


Figure 14. pH change with lime addition

6.3.2 Mechanical performance

Immediate bearing capacity

In the case of use in a form layer, the punching tests are carried out on specimens compacted with the Proctor Normal energy and at the maximum foreseeable water content. When using the roadbed, the lift to be obtained during implementation must in no case be less than 20 IBI (immediate bearing index), so as to guarantee implementation without deformation of the layer. The minimum IBI values to be obtained for each type of material are specified in Table 11.

For pavement layers, punching tests are conducted on specimens at the water content of the study formulation and compacted with the modified Proctor energy.

Table 11. Immediate bearing index (IBI) minimum to obtain at the implementation of road sub-layers (from SETRA-LCPC, 2000)

Type of use	Subbase			Surface layer	
Soil classes	A_1 C_1A_1 B_5 C_1B_5	A_2 C_1A_2 B_6 C_1B_6	A_3 C_1A_3	A_1- A_2	B sandy
IBI minimum	20	15	10	20	30

Short-term mechanical performance

The short-term mechanical performance of sediment-based road materials should be evaluated according to the criteria defined in the SETRA-LCPC (2000) guide. The different tests as well as the decision thresholds necessary for the evaluation of the mechanical performances of the road sub-layers are indicated in Table 12.

Table 12. Mechanical behaviour of materials used in road sub-layers

	Use in subgrade		Use in subbase	
Behaviour of road material	Indicator	Decision levels	Indicator	Decision levels
Age allowing circulation on the layer	Resistance to single compression stress (Rc) at different ages	Rc ≥ 1 MPa	Resistance to single compression stress (Rc)	Rc ≥ 1.0 MPa (A*) Rc ≥ 1.2 MPa (B*) Rc ≥ 1.5 MPa (C*)
Early resistance to immersion	Rci after 28 days at 20°C	Rci/Rc60 ≥ 0.80 with a floor of VBs ≤ 0.5	Rci after 28 days at 20°C	Rci/Rc60 ≥ 0.80 for a sample with MBV ≤ 0.5
	Rci after 32 days of total immersion in water at 20°C	Rci/Rc60 ≥ 0.60 with a floor of VBs ≥ 0.5	Rci after 32 days of total immersion in water at 20°C	Rci/Rc60 ≥ 0.70 for a sample with MBV > 0.5
	Rc60 after 60 days at 20°C		Rc60 after 60 days at 20°C	
Early resistance to frost	Resistance under direct traction Rt or indirect Rti.	Rt ≥ 0.20 MPa or Rti ≥ 0.25 MPa	Resistance under direct traction Rt or indirect Rti.	Rt ≥ 0.20 MPa or Rti ≥ 0.25 MPa

* The letters define the levels of aggressiveness of the traffic on site (SETRA-LCPC, 2000)

Long-term mechanical performance

In addition to the required IBI values, to be used as underlayers, the materials must have good long-term mechanical performance to ensure the smooth running of the pavement under traffic. This property is evaluated by tests of crushing cylindrical specimens in simple compression and diametric compression. The mechanical characteristics are measured at 28 and 90 days with 'fast curing' road-based hydraulic cements and binders (LHR) at 180 days with 'normal curing' LHRs. The E-Rt pair, measured at 90 or 180 days, is the basis of the definition of the mechanical class of the treated material. It makes it possible to locate it in the abacus of FIG. 15 and to determine the mechanical class of the material using Table 13. For example, for a layer of form, it is necessary to obtain at least a mechanical class of 5

Table 13. Determination of the mechanical class of a soil treated according to its mechanical characteristics and its method of preparation

Central processing	Field processing	Mechanical class
Zone 1	-	1
Zone 2	Zone 1	2
Zone 3	Zone 2	3
Zone 4	Zone 3	4
Zone 5	Zones 4 and 5	5

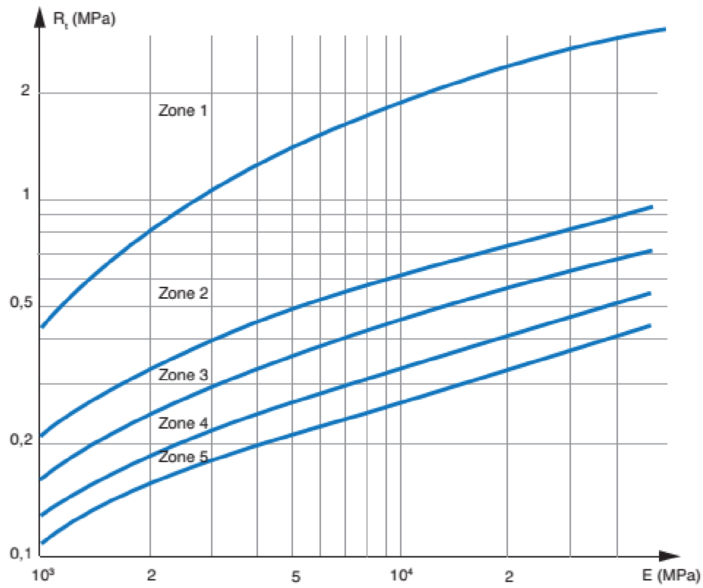


Figure 15. Classification chart for road structure materials with hydraulic binders (SETRA-LCPC, 2000)

6.3.3 Environmental acceptability

At this stage of the study, environmental characterisation is about the road material and the additional constituents used in formulating it (for example, a grain size corrector). These materials must be characterised according to their leaching and/or percolation behaviour and according to their intrinsic pollutant content depending on the intended application.

For underlayment applications, level 1 characterisation based on leaching tests according to standard NF EN 12457-2 and total content analysis with a variability study should be carried out. The comparison of the measured concentrations with the leaching thresholds defined in the SETRA guide makes it possible to judge the environmental quality of materials (see Tables 7, 8 and 9).

For certain type 1 applications (embankment in the coated zone), material conformity can be evaluated with respect to the level 2 characterisation based on percolation tests (standard NF CEN/TS 14405).

In addition, the guide specifies that any non-hazardous fraction resulting from a hazardous waste treatment operation - excluding any stabilisation operation - is considered a non-hazardous waste. Stabilisation, dilution or mixing of waste is prohibited for the sole purpose of meeting the acceptability criteria set out in SETRA (2011). The deposits of dredged sediments that can be used in road structures are for the construction of roadways whose mechanical characteristics comply with the standards of current use specifications and whose environmental characteristics meet the criteria of acceptability defined in the guide.

The road materials formulated as part of the laboratory study must be subject to environmental characterisation through the performance of leaching tests on crushed materials according to the NF EN 12457-2 standard and monoliths according to the NF standard EN 15863.

The principle of the leaching test according to standard NF EN 12457-2 is to expose the ground material to a leaching agent (distilled water) for 24 hours and then analyse the eluate obtained (see Figure 16). To do this the sample of 90 ± 5 g is introduced into a 2L HDPE bottle with distilled water (so as to obtain an L/S of 10 L.kg-1). The bottle is then shaken by inversion for 24 hours (± 30 min). For each eluate, the pH, redox potential, conductivity and temperature are measured. Samples are then taken to the laboratory for elemental analyses. The pollutants we need to look for are those in the Acceptability Guide for Alternative Materials in Road Technology (SETRA, 2011)

Figure 16. Main steps of a leaching test carried out according to standard NF EN 12457-2

The leaching tests on raw road materials are carried out according to standard NF EN 15863, also called DMLT for Dynamic Monolithic Leaching Test. The test portion has no defined shape but must be regular and measure at least 40 millimetres in all dimensions. The test makes it possible to determine the release of the constituents coming from the monolith under dynamic conditions as a function of time by relying on the experimental set-up described in Figure 17. The renewal of the leaching agent is done at different pre-established periods and reported in Table 14. At the end of each period, the eluate is separated from the monolith and the pH and conductivity of the fraction collected are measured before filtration (0.45 µm cellulose acetate filters) and conditioning the samples for analysis. The pollutants sought are similar to those covered by the Acceptability Guide for Alternative Materials in Road Technology (SETRA, 2011).

Table 14. Time intervals applicable to the collection of eluates in LMDA (Based on norm NF EN 15863)

Step/Fraction	Time interval duration	Duration from test beginning
1	6 h ± 15 min	6 h ± 15 min
2	18 h ± 45 min	1 day ± 45 min
3	1 day and 6 h ± 1 h	2 days and 6 h ± 2 h
4	1 day and 18 h ± 2 h	4 days ± 4 h
5	5 days ± 6 h	9 days ± 10 h
6	7 days ± 8 h	16 days ± 18 h
7	20 days ± 8 h	36 days ± 42 h
8	28 days ± 24 h	64 days

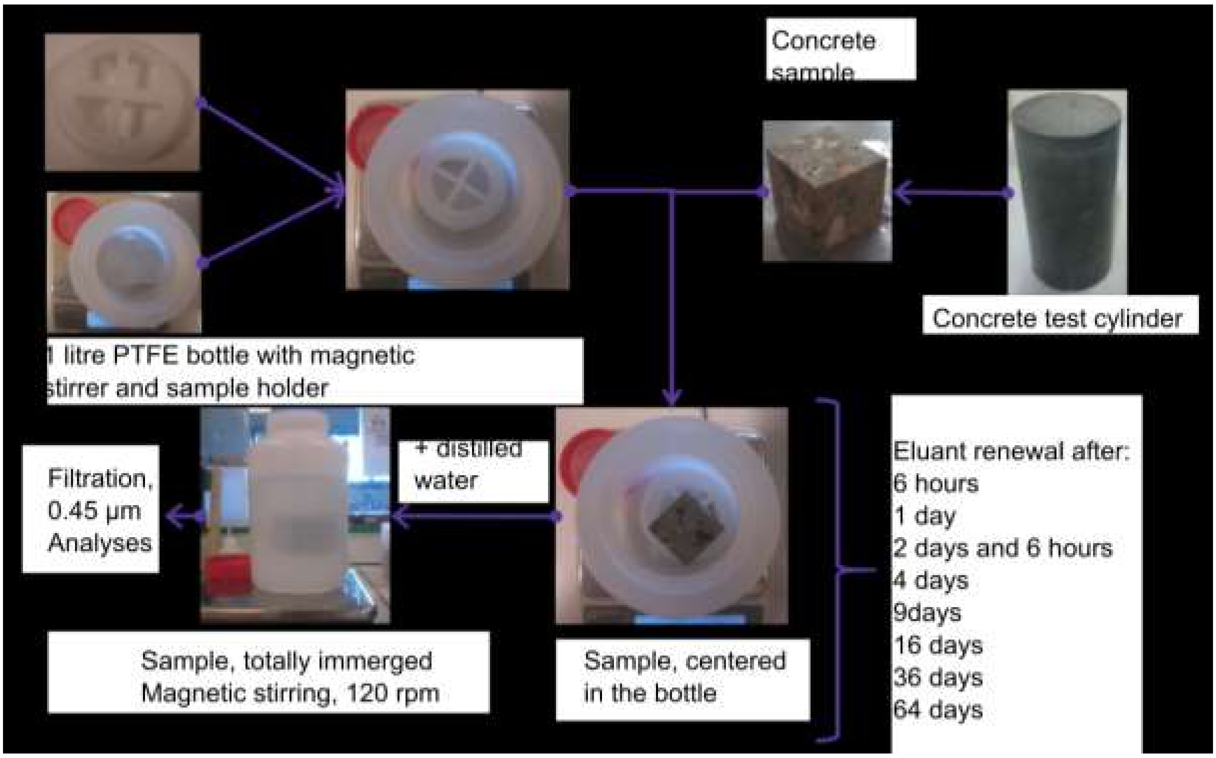


Figure 17. Experimental set-up for leaching on monolith with leaching agent renewal

6.4 Design and follow-up of an experimental board

6.4.1 Design of the experimental board

The laboratory study consists in setting up an experimental plate in order to study the mechanical and environmental behaviour of sediment-based road material (Figure 18).

A test board is a small structure (1 - 2 m^2) in which the road material is used in conditions representative of the road use studied (thickness of the studied layer, compactness, slopes, etc.). and subjected to controlled exposure

conditions that can be used to reproduce fixed or accelerated external conditions (e.g. rainfall in 6 months), or specific rainfall qualities for certain scenarios (e.g. acid rain). The experimental board is equipped to collect the percolated water through the structure as well as the runoff water separately.
The surface of the studied layer must have a slope of 2.5%. The thickness and permeability of the studied layer must be chosen to reproduce the structure of the most unfavourable structure for the study of the leaching behaviour of the tested road material.
A control board made from ordinary materials should be used. It reproduces the same structure but uses, instead of the tested road material, a natural material taken as reference (preferably siliceous). It validates the operation of the experimental board incorporating the tested road material.

Figure 18. Experimental board implemented for an application in road sub-layer

6.4.2 Geotechnical and environmental monitoring

Monitoring the experimental board consists in taking water samples and cores of road material in order to track pollutant emissions and the mechanical performance of the road material over time over a minimum period of 6 months. Taking cores of the materials of the structure at the end, or even during the follow-up of the experimental plate, is recommended to validate the formulations developed in the laboratory.

Mechanical behaviour is evaluated from core samples during or after the experiment, using simple compression, tensile and elastic modulus tests. The compressive strength of the road material is evaluated according to standard NF EN 13286-41. The tensile strength is determined according to standard NF EN 13286-42. On the basis of the results obtained for tensile strength and elastic modulus, the mechanical class of road material is determined according to standard NF EN 13286-4.

The environmental monitoring of the experimental plate will have to be carried out according to the recommendations of the guide of design and follow-up of the experimental pads and lysimetric tests of the

ADEME (2010). Thus, the water analyses are carried out on samples filtered at 0.45 µm and acidified. The main parameters to be determined are pH, conductivity, redox potential, temperature, anions (chlorides, sulfates, fluorides), cations (major elements: Ca, Mg, Na, etc.), trace elements (As, Ba, Cd, Total Cr, Cu, Hg, Mo, Ni, Pb, Sb, Se, Zn) and organic pollutants.

Other parameters can be monitored depending on the applications envisaged and the quality of the materials used. The parameters studied can be selected by comparison with the regulations: The Order of 9 September 1997 concerning non-hazardous waste storage facilities or the Decree of 9 August 2006 concerning the levels to be taken into account during a release analysis in surface waters or marine sediments, estuarine or stream extracts or channels falling respectively under headings 2.2.3.0, 4.1.3.0 and 3.2.1.0 of the nomenclature appended to Article R. 214-1 of the Code of the Environment.

The environmental monitoring carried out on the boards must be completed by performing leaching tests on samples of core material from the experimental board. From these laboratory tests at the end of the monitoring we can characterise the behaviour of the pollutants in the altered matrix under the conditions of the study scenario.

Thus, leaching tests must be carried out on the cores according to standard NF EN 12457-2 (on crushed material). This standard applies to fragmented waste and sludge with a grain size of less than 4 millimetres, where the grains can be reduced to meet this criterion. To apply this standard, the solids content of the material must be greater than 33%. For this standard, it is assumed that equilibrium (or near equilibrium) is reached during the test.

Leaching tests on road materials can also be carried out according to standard NF EN 15863. The test principle is to expose a monolith to a lixiviant (demineralised water) with stirring (magnetic stirring at about 120 rpm). The leaching agent is renewed to meet the exposure times recommended in the standard over a period of 64 days. Each time the leachate is renewed, it is filtered using a vacuum filtration device and a 0.45 µm cellulose acetate filter. For each eluate, the pH, redox potential, conductivity and temperature are measured.

The pollutants sought in these leaching tests are similar to those covered by the Acceptability Guide for Alternative Materials in Road Technology (SETRA, 2011). The recommended analyses (trace elements, chlorides, sulfates) concern the fraction extracted from the cores taken at 60 and 360 days and are expressed in mg/kg of dry stabilised waste. The leaching limit values of the SETRA guide make it possible to judge the environmental acceptability of materials according to standard NF EN 12457-2.

7. Phase 3: Field work

7.1 Objective

The field phase is essential to validate the results of the mechanical and environmental feasibility study carried out in the laboratory. In its content, this phase includes the realisation of an instrumented operational work on a limited but significant scale. This experimental level makes it possible to (i) overcome the effect of scale, (ii) verify the technical feasibility of implementation and the mechanical strength of the material in real conditions and (iii) compare the quality of percolation of the structure with those of the receiving site. The structure will be mechanically and environmentally monitored for a minimum of one year. The compliance of results obtained in the field with laboratory tests and technical and regulatory references will validate the technical and environmental feasibility of the targeted use sector.

7.2 Procedures and preliminary studies

7.2.1 Regulations on transit and/or treatment facilities

A material intended for a civil engineering application has characteristics that should be modified according to the type of use. The storage step can make these changes possible.

A significant water content, such as that encountered in sediment, has a major disadvantage for a valuation in road technology. Pre-treatment will therefore be necessary to reduce the water content of the material. The different techniques use, for example, vacuum consolidation, settling tanks, centrifuges, evaporators, press filters and band filters. These dewatering techniques make it possible to reduce the volumes to be treated by eliminating up to 50% of the interstitial water contained in the sediments which contain 50 to 90% of them depending on the dredging technique used.

In the case where the client is a sediment operator and if a transit and/or treatment facility is required for the recovery operation, the impact study is mandatory under the ICPE [1]legislation. The content of the Impact Study is specified in article R122-5 of the Environment Code. In addition, there is a DREAL guide of June 2012 (part II C dedicated to the impact assessment of an ICPE) as well as an INERIS guide of August 2013 established for the ICPE. These guides can serve as a reference and help to prepare an impact study.

The circular of 4 July 2008 relating to the procedure concerning the management of sediments during works or operations involving dredging or sea and river flushing stipulates that an ICPE declaration or authorisation is necessary:

- when the surplus materials that can be marketed consist of products minerals (sands, gravel, pebbles) and
- conveyed to a transit station with a storage capacity of more than 15 000 cubic meters (Declaration) or 75 000 cubic meters (Authorisation) (item 2517, see 2515 of the ICPE nomenclature).

Decrees no. 2009-1341 of 29 October 2009 and no. 2010-369 of 13 April 2010 modified in depth the nomenclature of the classified installations. The administrative classification of the waste treatment activities no longer concerns the source of the waste, but its nature and dangerousness, consistent with the importance of the dangers and inconveniences generated by the treatment of such waste.

The circular of December 24, 2010 sets the terms of application of these various decrees. Thus, sediment disposal sites are treated as waste storage or transit facilities and are subject to authorisation under ICPE legislation.

Table 15 groups the potential headings covered by the ICPE nomenclature.

[1] ICPE is the French status for sites of potential environmental concern. Such sites are subjected to specific regulations and authorisations for operation

The Water Framework Directive (2000/60/EC) and its daughter Directive on Groundwater (2006/118/EC) impose a target result, good water status by 2015 and the progressive reduction and elimination of discharges, emissions and losses by 2020; hence the need to set up control networks on groundwater bodies and particularly on point pollution. This directive is cited here in the context of on-land sediment management. Whether they are potentially polluted or not inert because of their salt content, the deposition of these sediments implies the establishment of groundwater monitoring measures at the disposal sites, with a view to controlling and eliminating discharges. In this respect, we should also recall that this type of rejection is regulated by the Decree of 9 August 2006 and its R1/R2 thresholds.

With a view to using dredged sediments, the temporary deposit on land and pre-treatment phase cannot exceed 3 years. This deadline stems from the definition given by the decree of 09/09/97 on ISDNDs (article 1).

Moreover, given the nature and behaviour of dredged sediments, items 2716 and 2791 of the ICPE nomenclature, relating to transit and non-thermal treatment activities (dewatering phase of sediments), are the most relevant for management. on land recoverable sediments.

Table 15. Headings potentially covered by the ICPE nomenclature

Sediment type	Activities		ICPE section no.
Inert sediment	Transit	Pulverulent	2516
		Non-pulverulent	2517
	Milling, crushing		2515
	Screening, sieving, etc.		
	Storage		L541-30-1
Non-hazardous sediment	Transport		2716
	Storage		2760-2
	Heat treatment		2771
	Non-heat treatment		2791
Hazardous sediment	Transport		2717/2718
	Storage		2760-1
	Heat treatment		2770
	Non-heat treatment		2790

7.2.2 Conducting an impact study

On-land management of dredged products can cause pollutants to be released into the environment. Although every precaution is taken to limit impacts on the environment and human health, risks for both are always possible. To ensure that these risks are negligible and socially acceptable, environmental and health risk studies are strongly recommended, although there is no regulatory obligation on this subject. The approach is also intended to integrate environmental concerns into the project design and to inform and authorise the environmental authority responsible for reviewing the project.

The main steps of a risk assessment are:

- A review of existing data on the study area. At this stage, data are presented on the concentrations of pollutants, in sediments and water where appropriate, which constitute the initial state;

- An inventory and the choice of pollutants. This step consists of deciding on the list of pollutants selected for the study and on their concentrations;

- Hazard identification and the dose/response relationship. In this step, the Toxicity Reference Values of the pollutants chosen in the previous step are considered in an argumentative manner;

- An estimate of the exposures. This takes place in several portions:

(i) the reasoned choice of the exposure routes selected (ingestion, skin contact);

(ii) the description of the methods and tools used to determine the concentrations in the various environmental media (sediments, water, flora, fauna, etc.) coming into contact with humans. At this stage, the baseline data in the sediment and in the water, if applicable, for the concentrations of the pollutants studied are introduced;

(iii) the definition of exposure scenarios that specify the target populations, the duration of exposure, food ration assumptions, etc.

(iv) the calculation, for target populations, of the quantities of pollutants absorbed in the form of an exposure dose.

- The characterisation of the risk. For toxic effects with thresholds, it consists in calculating a hazard quotient (QD) by comparing the quantities absorbed with the Toxicity Reference Values (TRVs). For effects without threshold, it consists of calculating an Individual Risk Excess (ERI) to develop a cancer

- The analysis of the uncertainties of the risk characterisation.

The risk assessment concludes with a conclusion in which the results are summarised, commented on and put into perspective.

<u>Global approach</u>

In general, whatever the methodology followed, a risk assessment takes into account the coexistence of one or more sources of danger (D) and one or more potential targets (C) likely to be affected by the source. of danger. Risk assessment is about looking at the source, the target and the potential interactions between the source and the target. These interactions exist via the transfer pathways (T) that occur between D and C. These interactions can be schematised in the following manner.

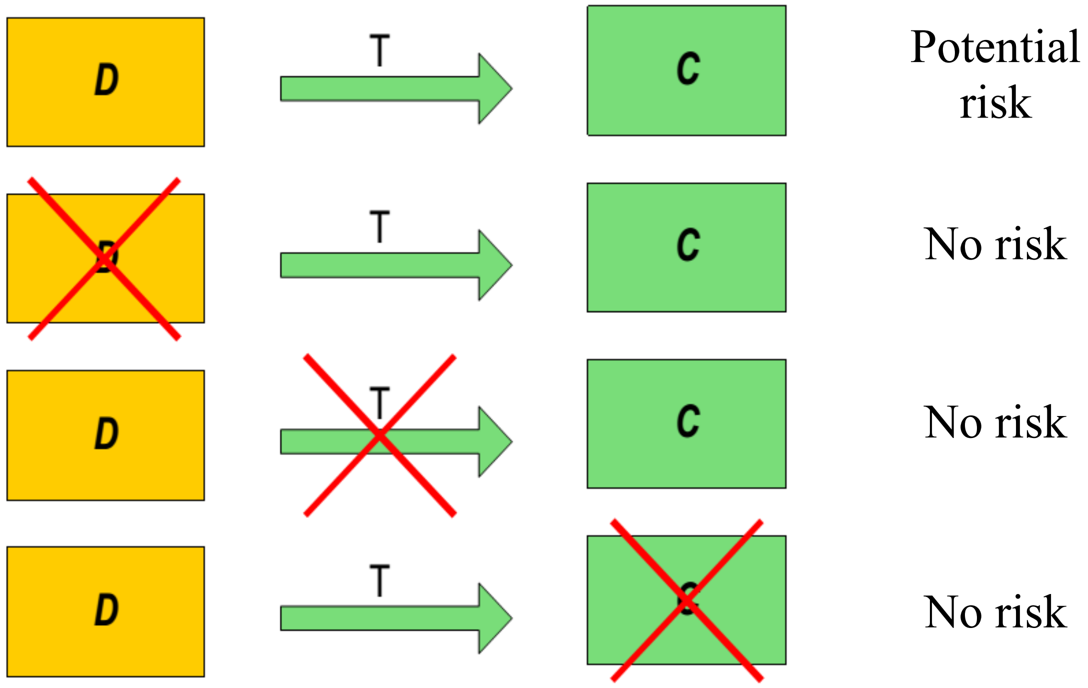


Figure 19. Basic principle of risk assessment

In the absence of a source of danger, it is obvious that any risk for the target can be excluded. Similarly, in the absence of a target, the source of danger is not a problem.

In the case where there is no transfer path between the source and the target, the risks may also be excluded, even if they are close to each other. Any risk assessment begins logically with the inventory of sources of danger and targets, in order to eventually establish their potential interactions. These interactions are then represented in the form of a conceptual diagram. Targets and transfer routes must be determined jointly. This makes it possible to avoid using means that might prove to be disproportionate in relation to the seriousness and/or the actual complexity of the situation. To this end, an iterative approach to the assessment of health and environmental risks is implemented. This approach considers the situation in the broadest manner at first and then narrows to become more and more precise, tending towards the real situation.

Thus, from the beginning of the study, the modelling of the studied phenomenon is simplified by taking into account various hypotheses. This approach is consistent from the moment the assumptions are conservative, that is to say that they consider a situation more unfavourable for the environment or the health than in reality (example: it is supposed that the concentrations in contaminants in a lake are maximum for the entire volume, rather than considering a concentration gradient within the body of water). The risks incurred by the targets are then estimated. In the case where these risks are non-existent for the environment or for health, the absence of risks related to the phenomenon or the situation studied can be concluded. In the opposite case, modelling will have to tend more towards reality. This can be done in different ways:

- By means of documentary research and/or complementary field investigations, the latter aimed either at directly raising hypotheses or at serving as a database for modelling;

- By means of a complexification of the model (taking into account physicochemical phenomena, improvement of the knowledge of the behaviour of the target, etc.)

This iterative approach can be summarised by the following logic diagram.

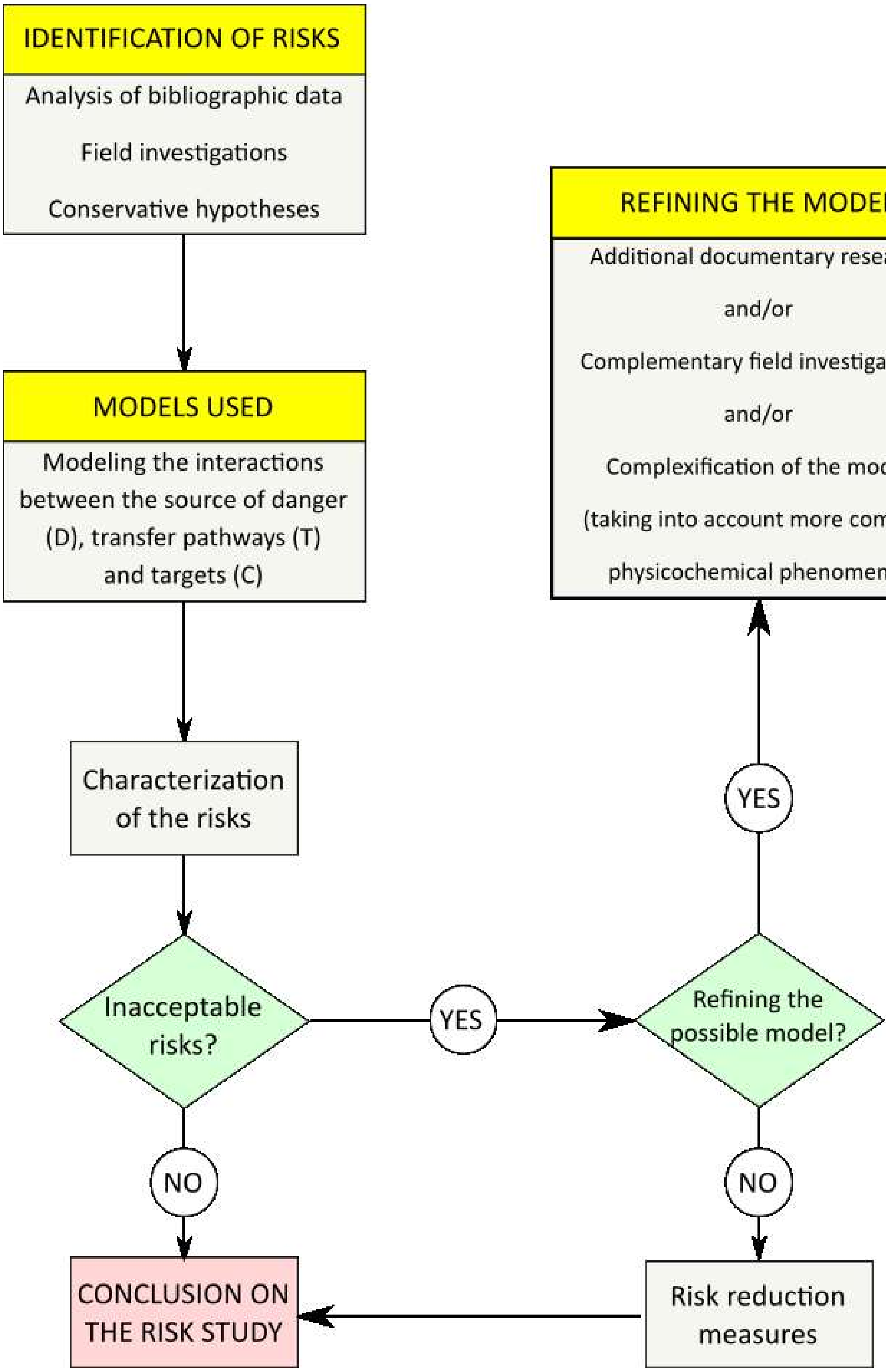


Figure 20. Iterative approach to risk assessment

Under the principle of proportionality, the means implemented to model the situation must be adjusted to the complexity and/or seriousness of the situation studied. In some cases, there is a time when modelling reaches its limits because of the complexity of the phenomenon (or a lack of data or scientific knowledge) before the absence of risk has been demonstrated. Ultimate control can then be achieved in the form of field measurements or laboratory tests. In the event that these tests or measures indicate inadmissible risks, preventive measures must be implemented to eliminate these risks. In some cases, whether for financial, technical or time-related reasons, it may be more interesting to propose prevention measures than to push modelling too far.

Environmental risk assessment

The assessment of the chemical risk in the environment must make it possible to estimate whether the presence of a given contaminant in the natural environment poses an immediate or future risk for the environment. Several methods of assessing chemical risk exist. The one used is based on the European methodology, implemented by Regulation (EC) No. 1488/94 of the European Union and detailed in the European Methodological Guide 'Technical Guidance Document' (ECB, 2003), used as a document reference.

The two basic assumptions of this methodology are:

1) The protection of the species of an ecosystem protects its structure and therefore its functioning;

2) The protection of the most sensitive species allows the protection of the entire ecosystem.

As indicated on the below, the approach of evaluation of the chemical risk in the environment relates two concepts:

- The assessment of the exposure of ecosystems, which is based on the measurement of the concentration of a substance in a given compartment of the environment (freshwater, marine water, sediment, biota). This concentration can also be estimated from appropriate models. This step leads to the establishment of Predicted Environmental Concentration (PEC);

- The assessment of the danger, which consists of characterising the ecotoxicity of a substance to establish its predicted no-effect concentration (PNEC). This is the maximum concentration that does not have any deleterious effects on the natural environment. This concentration may vary depending on the compartment of the environment; its relevance depends on the abundance and nature of the ecotoxicity data available to establish it. The lower the no-effect level of a substance, the more harmful it is to the natural environment. For a number of substances on the DCE priority list, there are regulatory threshold values called EQS (Environmental Quality Standards), which are derived from PNECs.

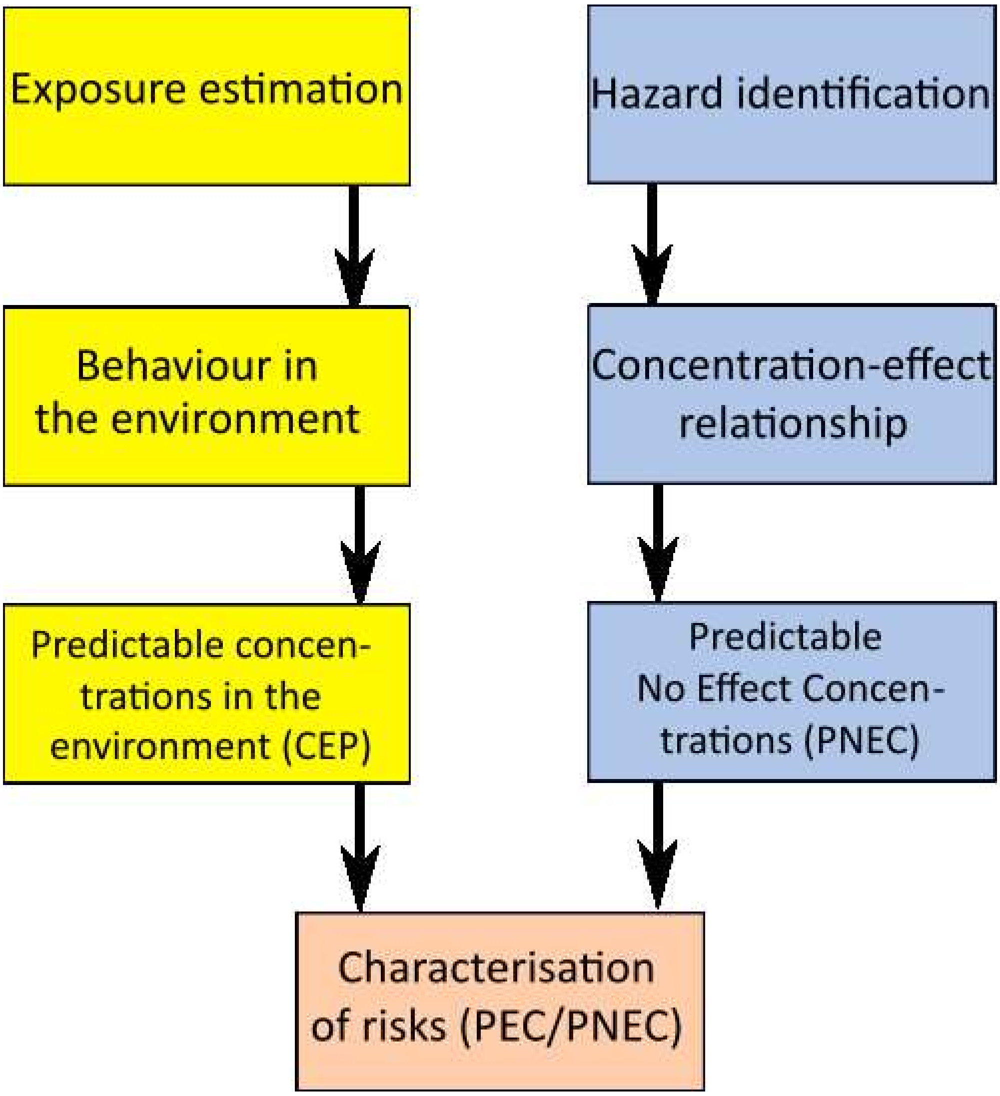


Figure 21. Scheme of the evaluation of the chemical risk in the environment (from Marchand and Tissier, 2005)

Following these two steps, the risk assessment, as such, is carried out by confronting the CEP and the PNEC. Three cases can then arise:

- PEC> PNEC: The exposure value exceeds the threshold value; there is a risk for the environment. It is possible, however, that the risk is overvalued. A refinement of knowledge regarding the CECs or PNECs may be necessary;

- PEC <PNEC: the exposure value is below the threshold value; there is no risk for the environment. This is true if the PEC is systematically overvalued and if the PNEC is systematically undervalued;

- PEC ≈ PNEC: the exposure value is similar to the threshold value; the risk cannot be determined in the current state of knowledge. PECs and/or PNECs need to be recalculated more precisely (with more data, more suitable methods) to be able to rule on the risk.

PNECs are calculated by expert organisations, such as INERIS in France. The methodology used to estimate PNECs is described in the Technical Guidance Document (ECB, 2003). According to available data, there are freshwater, marine, sediment and oral PNECs (secondary poisoning of predators by their prey). All these threshold values are extrapolated from experimental results, assigned a variable uncertainty factor according to the quality and the quantity of the data necessary for the calculation.

Studies carried out as part of the SEDIMATERIAUX approach were carried out from the PNECs of the substances from the INERIS toxicological datasheets.

Health risk assessment

Health risk assessment has been defined as 'the evaluation of information on the intrinsic hazard of substances, the degree of exposure of humans to these substances and the characterisation of the resulting risk' (National Research Council, 1994).

The health risk assessment must be in accordance with the framework defined in the general guides of the National Institute of Health Surveillance (INVS, 2000) and the implementation methods described by the methodological guide for the evaluation of the health risks of studies. The impact of ICPE established by INERIS (INERIS, 2003). Likewise, it must take into consideration the existing technical guides for the sectors studied, notably the 'Provisional Technical Guide on the Acceptability of Alternative Materials in Road Engineering'.

This type of approach must lead to a structured analysis in which the available information is collected in the current state of scientific knowledge, ordered and evaluated in order to quantify risks in a transparent manner.

Thus, the study of health risks carried out is broken down into 4 inseparable stages detailed and synthesised below:

1. Identify sources of danger: The first step is devoted to the characterisation of the site and its environment. A qualitative and quantitative inventory of the contaminants present in the air, soil and water is made to select the 'tracer' contaminants for health risks;

2. Evaluate the dose (concentration) - response (effects) ratio: In this step, the impact and severity of the health effects are estimated for each selected contaminant (toxicological reference value analyses, regulatory values and/ or guide values (EU, WHO, etc.);

3. Evaluate Exposure: The objective is to determine the pathways of transfer of 'tracer' contaminants from the source to the target and to estimate the frequency, duration and importance of exposure (Daily Dose calculations). of Exposure: DJE).

This step involves a model for estimating the concentrations of contaminants in the various exposure media (water, aquatic organisms ...) in contact with humans;

4. Characterise the risks: This last step corresponds to the synthesis of the information resulting from the evaluation of the exposure and the toxicity in the form of a quantitative expression of the risk. Uncertainties are evaluated qualitatively according to their major or minor character and the interpretation of the results.

On the other hand, this evaluation is carried out by applying certain principles (according to INERIS, 2003): The precautionary principle, the principle 'according to which the absence of certainties, taking into account the scientific and technical knowledge of the moment, must not delay the adoption of measures to prevent the risk of serious and irreversible environmental damage at an economically acceptable cost;

- The principle of proportionality, ensuring that there is consistency between the degree of depth of the study, the degree of contamination and its foreseeable impact;

- The principle of specificity, ensuring the relevance of the study in relation to the use and characteristics of the site and its environment;

- The principle of transparency, implying that the choice of the assumptions, the tools to be used and the degree of deepening necessary are explained and coherent.

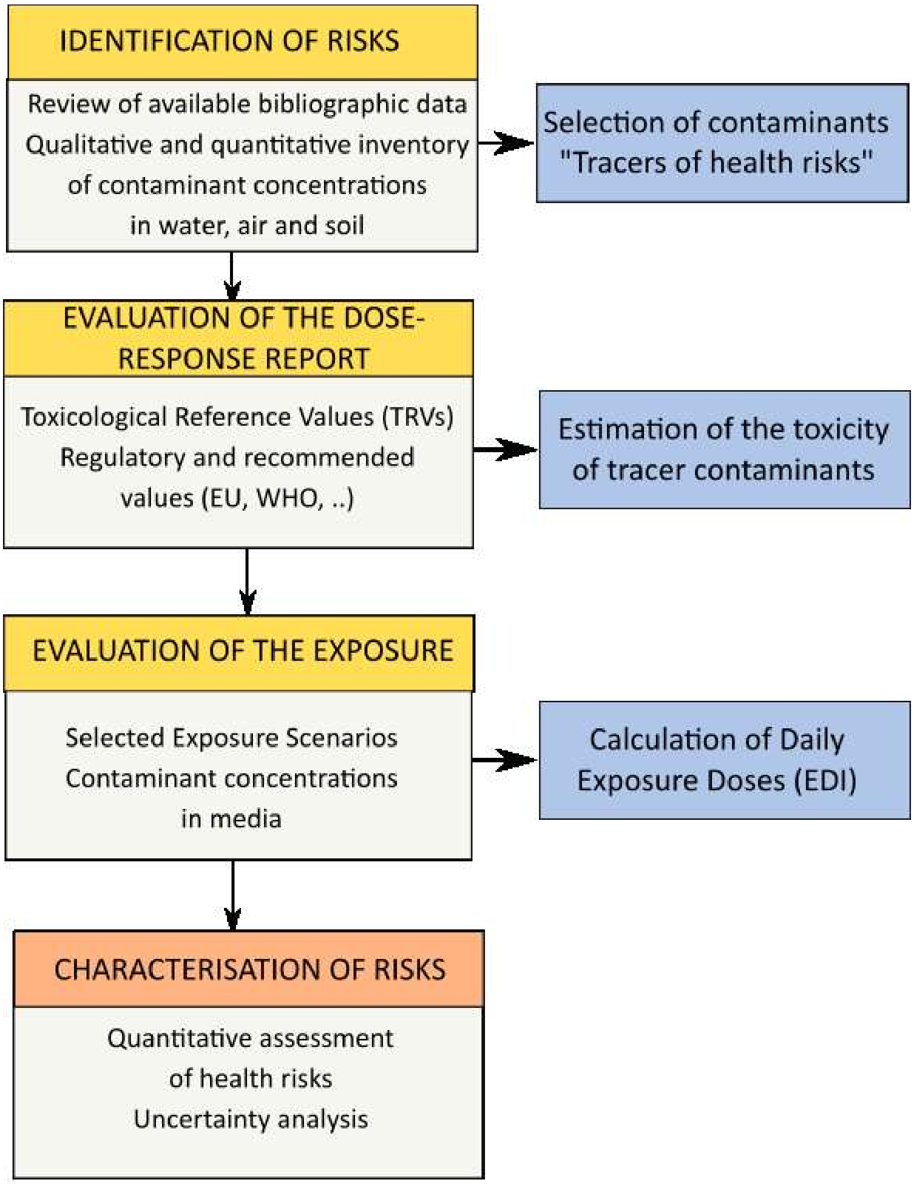


Figure 22. Stages of health risk assessment

The conceptual diagram

Exposure assessment is the determination of emissions, transfer pathways and rates of movement of substances, their transformation or degradation to assess the concentrations or doses to which populations are exposed or likely to be exposed.

Exposure to a substance depends on the behaviour of the materials to which it is attached, but also on the physical and chemical behaviour of the substance in the environmental compartments, its concentration, and the pathways and exposure conditions of the individuals in contact with the substance. All these parameters must be precisely determined to quantify the exposure of the target populations.

The purpose of the conceptual diagram is to summarise the sources, transfer routes and potential targets of the operation in question. Thus, each type of operation is the subject of a specific conceptual diagram depending on the environment in which the operation takes place, natural species present and human activities identified. The scheme then highlights the potential risks of the project for the environment and human health.

As an example, the figure below represents the conceptual diagram developed during the construction of the Freycinet 12 road in the perimeter of Dunkirk's Grand Port Maritime.

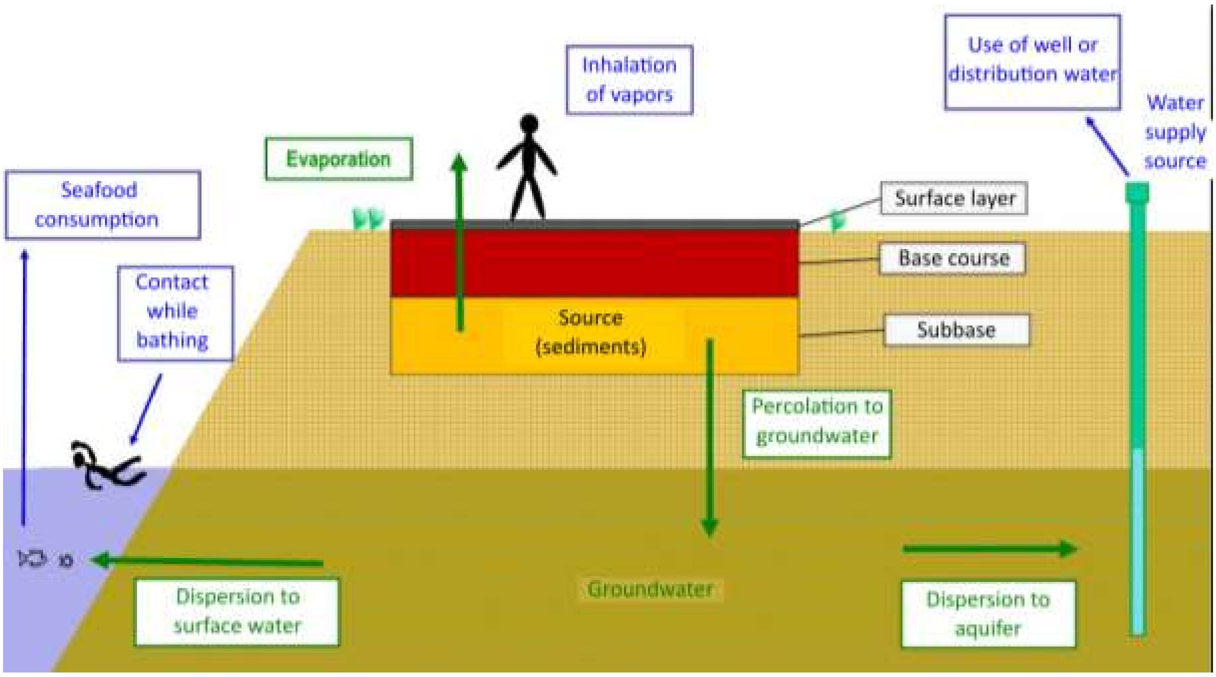


Figure 23. Conceptual diagram of the environmental and health risk assessment of a sediment-based road structure (From: IDRA Environnement)

7.3 Creating an experimental project

An experimental project including a plot of land was created to study the behaviour of the road material while avoiding the effects of scale that may appear during the performance of laboratory tests. On the experimental plot mechanical and environmental monitoring of the structure can be carried out to validate the corresponding laboratory studies. It is recommended to monitor the structure for a minimum duration of 12 months to take into account climatic variations (ADEME, 2010).

7.3.1 Technical characteristics of the roadway

From the work carried out by the Ecole des Mines de Douai on non-submersible sediments at the Grand Port Maritime of Dunkirk (GPMD) a formulation has been developed for using port sediments in road sub-layers (Achour, 2013). On the basis of the results obtained in the laboratory, an experimental road structure was made at the GPMD to validate the technical feasibility of the planned use. The experimental plot was constructed according to the recommendations of the ADEME guide (2010) and the design assumptions of the road structure were selected according to the traffic envisaged (Platform class: PF2, Traffic: 100 Pl/per day; 15 years).

The pavement structure has therefore been dimensioned accordingly and comprises:

- a wearing course 5 cm thick;
- a base layer 6 cm thick;
- a foundation layer based on 30 cm thick treated marine sediment;
- a natural soil constituting the PST.

7.3.2 Stages of creating the experimental pavement

During the implementation of the structure, a layer of 20 cm thick dredging sand was first placed on the platform and then stabilised with a grader. A second layer of fine sediments 10 cm thick was then spread. The two materials were homogenised using a spreader mixer. The following day, the lime was extended to a proportion of 1% (≈ 6 kg/m²). At this stage, the foundation layer was composed of dredged sand, non-submersible marine sediment and quicklime. After a cure period of 24 h, the hydraulic binder was spread with a content of 6% (≈ 36 kg/m²) before the materials were homogenised.

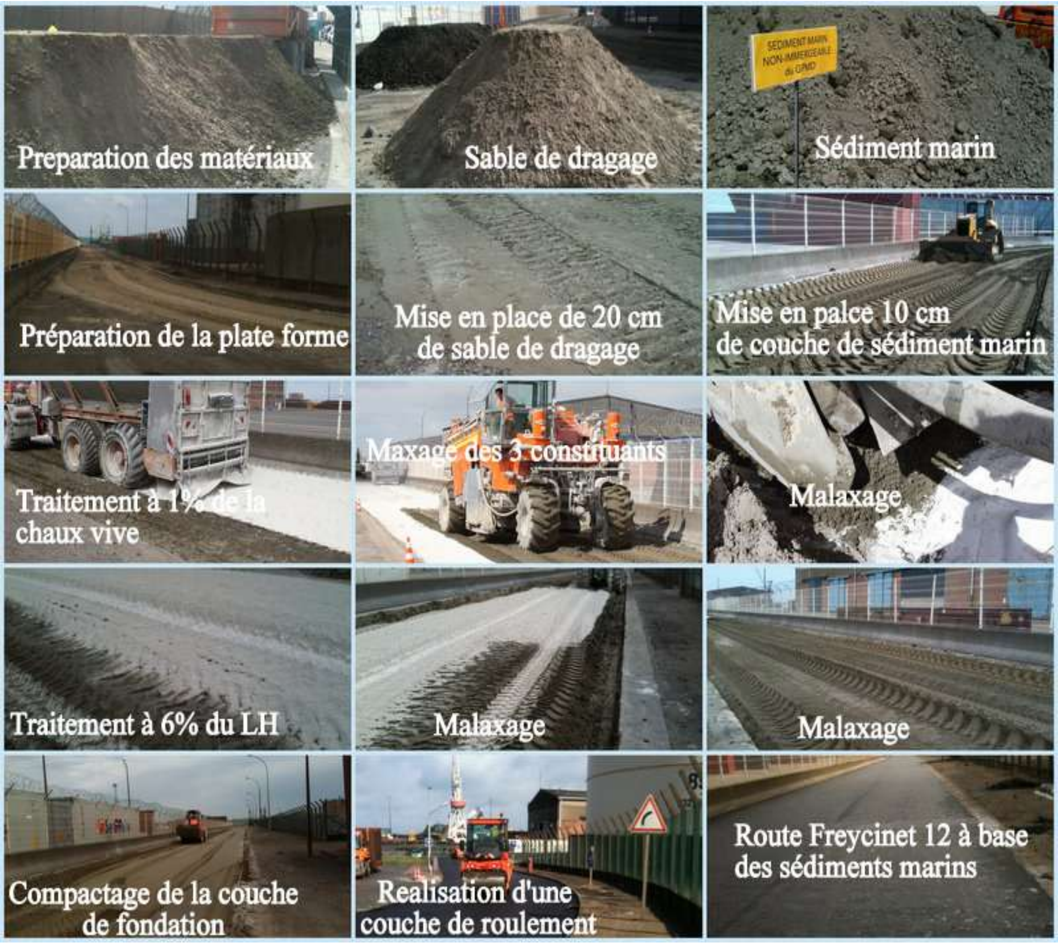


Figure 24. Stages of realisation of the experimental work based on harbour sediments

Captions :

Materials preparation	Dredged sand	Marine sediment
Preparing the road base	Placing a 20cm layer of dredged sand	Placing a 10cm layer of marine sediment
1% lime treatment	Mixing 3 constituents	Mixing
6% binder treatment	Mixing	Mixing
Compaction of the base course	Placing the surface layer	Marine sediment – based road

During the final stage of the design, the mixture (marine sediment, dredging sand, quicklime and hydraulic binder) was compacted with vibratory compactor (dynamic class V4). The water content being an essential parameter during the compaction process, it was measured using a gamma densimeter. The average water content recorded was about 10.4% and the dry density was 1.98 t/m^3. Following the compaction of the foundation layer, a 7-day rest period was imposed. Then the foundation layer was a measured in a deflection campaign. Finally, the base layer 5 cm thick was placed at the top of the foundation layer, followed by a wearing course 5 cm thick (in accordance with standard NF P 98 150-1). The construction stages of the experimental pavement are illustrated in Figure 24.

7.4 Mechanical and environmental monitoring

7.4.1 *In situ* monitoring of mechanical characteristics

The lift of the sediment-based road structure must be studied in situ by carrying out deflection measurements. The deflection measurement campaign should be performed at different road ages (e.g. 7, 60 and 360 days). In the field, the evaluation of the deflection is done by means of the point measurement of the vertical deformation of the structure under the load of a 13-tonnes vehicle axle, followed by a balance system such as the beam from BENKELMAN. The results of the deflection study are then compared to the mechanical tests performed on the pavement cores and to the results of the formulation study. The expertise of the data will allow appreciating the mechanical performances of the structure and the technical feasibility of the valuation of the marine sediment in road technique.

7.4.2 Environmental monitoring of the plot

The instrumentation for a structure prototype must be set up according to the design recommendations and followed up according to ADEME (2010) experimental studies and lysimetric tests. This guide specifies in particular the devices to be put in place during the environmental monitoring of the experimental pads.

Monitoring of percolation waters

Pollutants in dredged sediments are likely to be mobilised after rains and may represent a potential source of groundwater contamination. It is therefore necessary to monitor the quality of percolation water to characterise the environmental impact of the structure on the local environment.

Figure 25. Stages of conducting instrumented experimental work

Captions:

Preparation of the experimental test area	Placing an impermeable membrane
Placing infiltration piping	Placing the sediment-based subbase layer
Preparation of the installation of the observation well	Recovery of the percolation water of the subbase

In accordance with the ADEME guide (2010), the experimental plot includes a geo-membrane installation, a drainage system and a specific tank for the recovery of percolation water (Figure 25). The objective of this device is to recover percolation water during rainy episodes in order to carry out monthly monitoring of the concentrations of dissolved contaminants (Figure 26). Monitoring of the experimental plot should be scheduled for a minimum of one year to take into account the effect of seasonal variations on the pollutant transfer.

(1) (2) (3) (4)

Figure 26. Collection of percolation water at the experimental site (Achour, 2013). (1) and (2) Sample Collection, (3) and (4) Packaging.

Quality monitoring of the waters the receiving environment

The installation of a piezometer in the vicinity of the structure makes it possible to monitor the quality of the groundwater and to detect contamination related to the implementation of the structure. It is recommended to monitor the water quality of the receiving environment for a minimum of 12 months. Water samples are typically collected using a valve pump and field conditioned for laboratory chemical analysis (Figure 27).

(1) (2) (3) (4)

Figure 27. Water sampling at the piezometer. (1) Piezometer, (2) Valve pump, (3) Sampling device, (4) Sample conditioning

Monitored physical and chemical parameters

Water analyses are carried out on samples filtered at 0.45 µm and the main parameters to be determined are:

- pH
- Conductivity
- Redox potential (ORP)
- Temperature
- Anions (chlorides, sulfates, fluorides)
- Cations (major elements: Ca, Mg, Na, etc.)
- Trace elements (As, Ba, Cd, Total Cr, Cu, Hg, Mo, Ni, Pb, Sb, Se, Zn)
- Polycyclic aromatic hydrocarbons (PAHs)
- Dissolved organic carbon (DOC)

Regulatory framework for the assessment of water quality

The European Framework Directives on water (2000) and ambient air quality, as well as the French Grenelle Agreement on environmental objectives, imposed environmental monitoring and pollution mitigation. To achieve the objectives set, various regulatory tools are used (laws, plans, etc.). With regard to water resources and aquatic environments, the road network must comply with the regulatory objectives set in particular by the Water Framework Directive (WFD, 2000) and the Water and Aquatic Environments Act. (2006). The road operator must also comply with the local SDAGE (Master plan of development and water management), a planning instrument that provides, at the level of each watershed, the provisions to ensure the protection and the improvement the state of the waters and aquatic environments. The objective of the WFD is to reach the Good Condition of the Water Bodies by 2015 and, more generally, not to degrade the state of the water bodies. The

Good State is defined by the respect of thresholds, called "Environmental Quality Standards' (EQS), set for a certain number of physical, chemical and biological parameters:

- For surface water, the thresholds are listed in the Order of 25 January 2010 on methods and criteria for assessing the ecological status, the chemical status and the ecological potential of surface water.

- For groundwater, the thresholds are listed in the decree of 17 December 2008 establishing the evaluation criteria and the methods for determining the state of groundwater and significant and lasting trends in the degradation of the chemical status of groundwater. underground waters.

In addition, thresholds for the quality of surface waters used or intended for human consumption may also be used for interpretation of monitoring results. The threshold values are defined in the decree of January 11, 2007 relating to the limits and references of quality of raw water and water intended for human consumption mentioned in articles R.1321-2, R.1321-3, R1321-7 and R.1321-38 of the Public Health Code according to the summary of the regulations published by the Ministry of Ecology and Sustainable Development on 1 December 2011.

The World Health Organisation's (WHO) thresholds can serve as comparative values when there are no French regulatory values. In the case where there is no value for a specific compound, be it regulatory or management, then health risk calculations for a water ingestion scenario should be performed to determine a target value for the substance under consideration.

7.4.3 Specific tests after core drilling

Coring is a destructive test that gives much information about the condition of roadway layers. This sampling technique involves cutting and extracting a solid cylindrical sample from a pavement. From looking at the carrot, we know the state and nature of the road material. As part of the mechanical and environmental monitoring of the plot, two core drilling campaigns at 60 and 360 days are recommended to characterise the behaviour of the road material.

Environmental monitoring after 60 and 360 days

As part of the environmental monitoring, roadside core drilling campaigns are recommended at 60 and 360 days after completion of the work.

Leaching tests must be carried out on the cores according to standard NF EN 12457-2 (on crushed material). This standard applies to fragmented waste and sludge with a grain size of less than 4 millimetres, where the grains can be reduced to meet this criterion. To apply this standard, the solids content of the material must be greater than 33%. For this standard, it is assumed that equilibrium (or near equilibrium) is reached during the test.

Leaching tests on road materials can also be carried out according to standard NF EN 15863. The test principle is to expose a monolith to a lixiviant (demineralised water) with stirring (magnetic stirring at about 120 rpm). The lixiviant is renewed to meet the exposure times recommended in the standard over a period of 64 days. Each time the leachate is renewed, it is filtered using a vacuum filtration device and a 0.45 µm cellulose acetate filter. For each eluate, the pH, redox potential, conductivity and temperature are measured.

The pollutants sought in these leaching tests are similar to those covered by the Acceptability Guide for Alternative Materials in Road Technology (SETRA, 2011). The recommended analyses (trace elements, chlorides, sulfates) concern the fraction extracted from the cores taken at 60 and 360 days and are expressed in mg/kg of dry stabilised waste. The leaching limit values in the SETRA guide make it possible to judge the environmental acceptability of the materials according to standard NF EN 12457-2.

Mechanical behaviour study after 60 and 360 days

Mechanical behaviour is evaluated by simple compression, tensile and elastic modulus tests. The compressive strength of the 60-day and 360-day road sub-layer material is evaluated according to standard NF EN 13286-41. The tensile strength is determined according to standard NF EN 13286-42. On the basis of the results obtained for tensile strength and elastic modulus, the mechanical class of road material is determined according to standard NF EN 13286-4.

8. Synoptic of the SEDIMATERIAUX methodology

The methodology developed in the SEDIMATERIAUX approach comprises three main phases:

PHASE 1) CHARACTERISATION

PHASE 2) LABORATORY STUDY

PHASE 3) FIELD WORK

PHASE 1: Characterisation phase including regulatory (Phase 1A) and complementary (Phase 1B) analyses

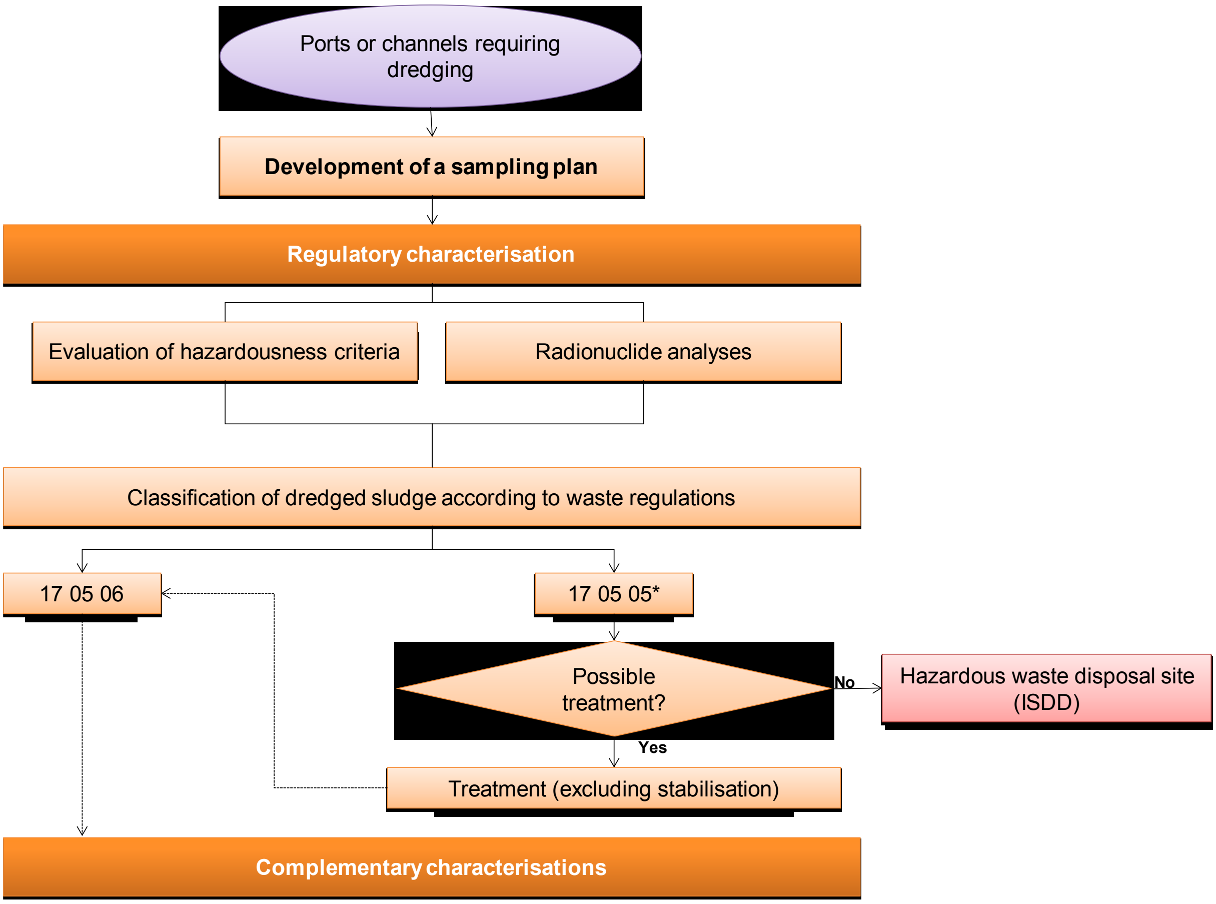


Figure 28 : PHASE 1A: Regulatory characterisations

PHASE 1B: Complementary characterisations

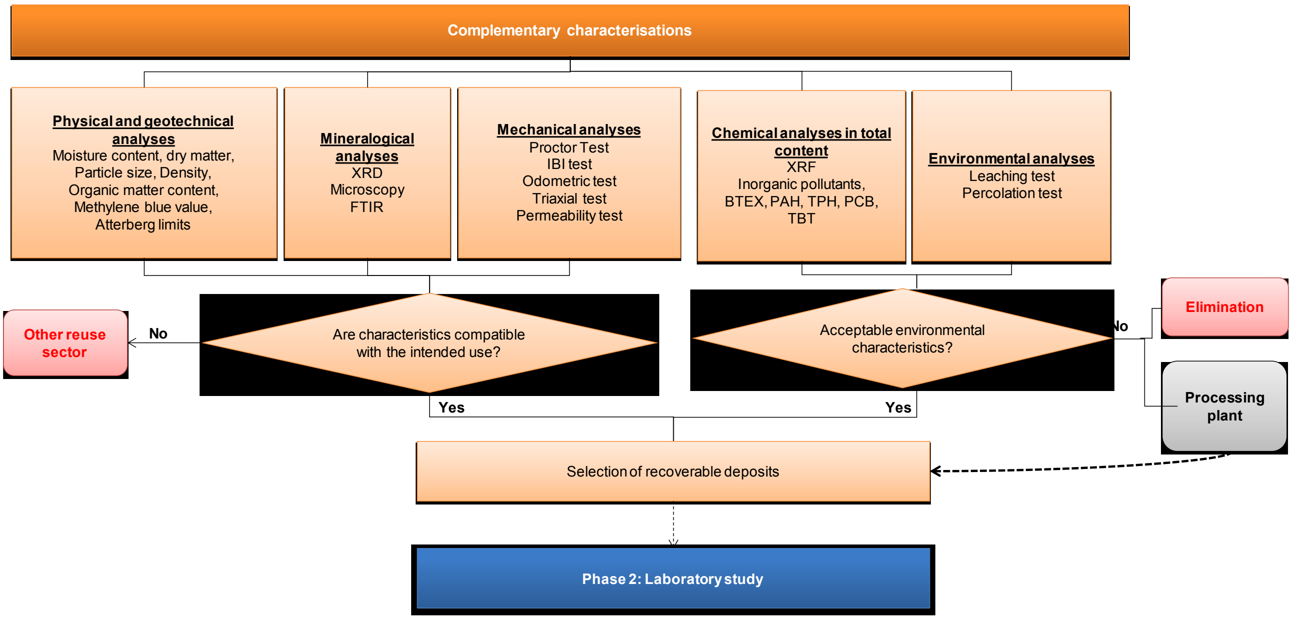


Figure 29: PHASE 1B: Complementary characterisations

PHASES 2 and 3: Phases of laboratory studies (PHASE 2) and field studies (PHASE 3) to validate the technical, mechanical and environmental feasibility of the project.

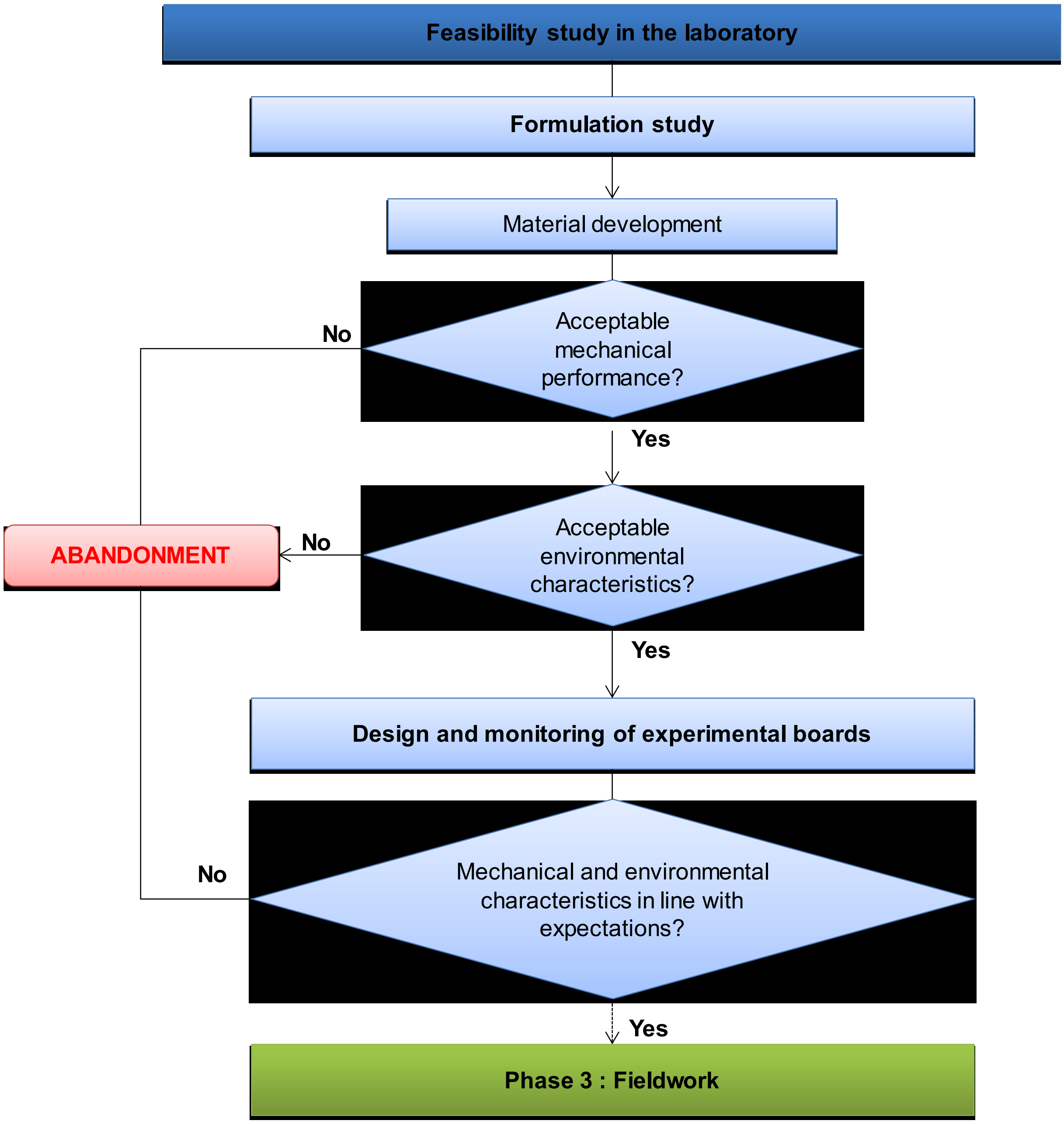


Figure 30: PHASE 2: Feasibility study in the laboratory

PHASE 3: Plan pilot field test (PHASE 3A: Procedures and preliminary studies, PHASE 3B: Pilot field test)

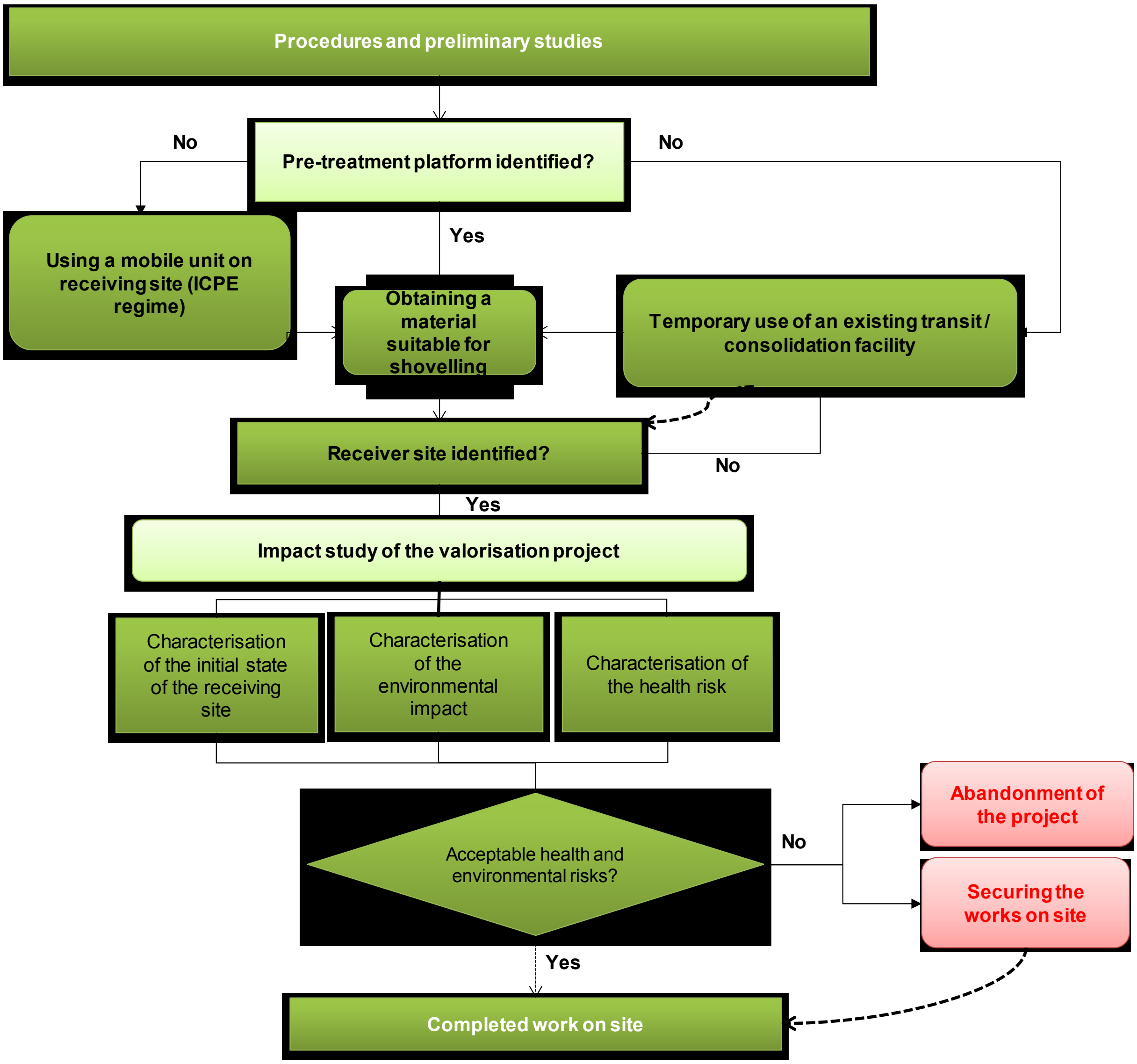


Figure 31: PHASE 3A: Procedures and preliminary studies

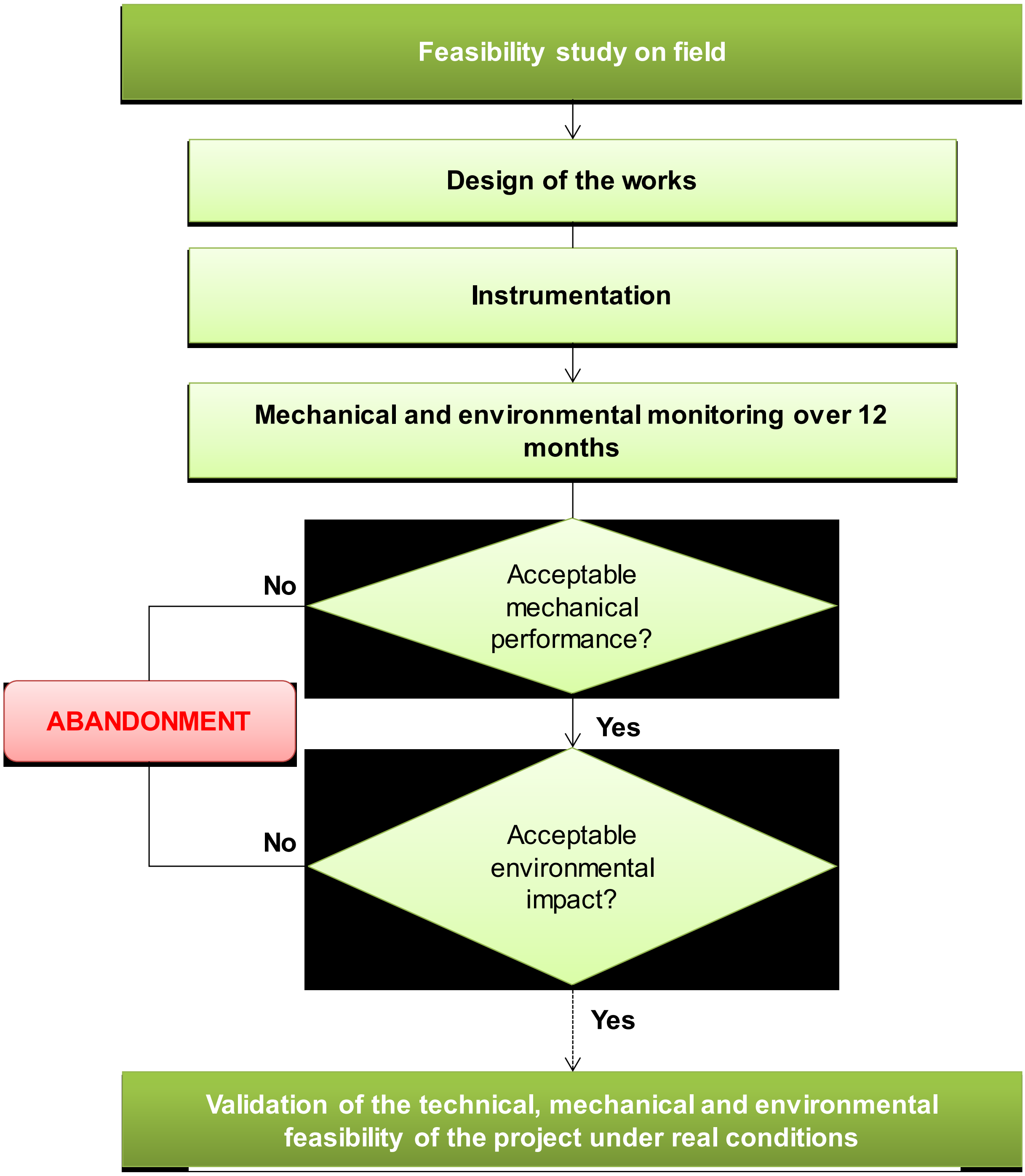


Figure 32: PHASE 3B: Pilot field test

9. Acronyms

Organisations

ADEME: Agence de l'environnement et de la maîtrise de l'énergie (French Environment and Energy Management Agency)

CD2E: Création et Développement des Eco-Entreprises (Creation and Development of Eco-Enterprises)

CE: Communauté européenne (EC: European Community)

CETMEF: Centre d'étude technique maritime et fluvial, le CETMEF a fusionné avec d'autres organismes dont le SETRA pour former le CEREMA (Centre d'études et d'expertise sur les risques, l'environnement, la mobilité et l'aménagement) depuis le 1er Janvier 2014
Technical centre for maritime and fluvial engineering, CETMEF merged with other organisations including SETRA to form CEREMA (Centre for studies and expertise on risks, the environment, mobility and development) since January 1st, 2014

CIMBéton: Centre d'information sur le ciment et ses applications (Information Centre on Cement and its Applications)

DREAL: Direction Régionale de l'Environnement, de l'Aménagement et du Logement (Regional Directorate for the Environment, Planning and Housing - decentralised French government agency)

EPA: Agence américaine de protection de l'environnement (US Environmental Protection Agency)

GPMD: Grand Port Maritime de Dunkerque (Dunkirk Maritime Port Agency)

INERIS: Institut national de l'environnement industriel et des risques (National Institute of Industrial Environment and Risks)

InVS: Institut de veille sanitaire (Institute for Public Health Surveillance)

LCPC: Laboratoire central des ponts et chaussées (Central Bridges and Roads Laboratory)

OMS: Organisation Mondiale de la Santé (WHO: World Health Organisation)

SETRA: Service d'études sur les transports, les routes et leurs aménagements (Study Board on Transport, Roads and their Facilities)

UE: Union Européenne EU: European Union

VNF: Voies navigables de France (French Waterways Board)

Technical terms

BTEX: Benzene Toluene Ethylbenzene and Xylene

CaO: Chemical formula of lime

C_c: Coefficient of curvature

CE50 (EC50): Effective concentration where 50% of maximum effect is observed

CE20 (EC20): Effective concentration where 20% of maximum effect is observed

COD: Carbone organique dissous (DOC: dissolved organic carbon)

COT: Carbone organique total (TOC: Total organic carbon)

C_u: Coefficient of uniformity

DCE: Directive cadre sur l'eau (WFD: Water Framework Directive)

DJE: Doses Journalières d'Exposition (ADI: Acceptable daily intake)

D_{max}: Maximum dimension in millimeters of the aggregates contained in a sample

DRX: Diffraction des rayons X (XRD: X-ray diffraction)

E: Elastic modulus

ERI: Excès de Risque Individuel (Individual Risk Excess)

FX: Fluorescence X (XRF, X-ray Fluorescence)

GTR: Guide des Terrassements Routiers (Guide to Road Groundwork)

H14: 'Ecotoxic': property of a waste which presents or may present immediate or delayed risks for one or more sectors of the environment (Directive 2008/98/EC of the European Parliament and of the Council)

HAP (PAHs): Polycyclic Aromatic Hydrocarbons

HCT (TPH): Total Petroleum Hydrocarbons

ICPE: Classified Installations for Environmental Protection (French Environment Code)

Ip: Plasticity index

IBI: Immediate Bearing Index

ISDI: Inert waste storage facility

ISDND: Non-Hazardous Waste Storage Facility

L/S: Liquid/solid ratio expressed in L/kg

LHR: Road hydraulic binder

MPa: Megapascal

N1/N2 and S1: Reference thresholds defined for the assessment of sediment quality (French Order of 9 August 2006)

NQE: Environmental quality standards

PCB: Polychlorinated Biphenyls (Polychlorobiphényles)

PEC (PNEC): Predicted no-effect concentration: This is the highest concentration of the substance without risk to the environment.

PF2: Platform class (see SETRA-LCPC guide, 2000) Classe de plateforme (cf. guide SETRA-LCPC, 2000)

Pl: Trucks and heavy vehicles

PST: Ground works support platform (Plateforme support de terrassement)

QD: Hazard ratio (Quotient de danger)

R1/R2: Reference thresholds defined for pollutants discharges into surface waters (French Order of 9 August 2006)

Rc: Direct compressive strength (Résistance en compression simple)

Rci: Indirect compressive strength (Résistance en compression indirecte)

Rt: Direct tensile strength (Résistance en traction directe)

Rti: Indirect tensile strength (Résistance en traction indirecte)

SDAGE: Master plan of development and water management (Schéma directeur d'aménagement et de gestion des eaux)

TBT: Tributyltin

TP: Civil works (travaux publics)

UT: Toxicity Unit (Unité Toxique UT = 100/CE50)

VBs Methylene blue value (Valeur au bleu de méthylène), which reflects the amount of clay minerals in aggregate samples

VTR Toxicological Reference Value (or TRV) (Valeur Toxicologique de Référence) is a health reference value defined by ANSES - a French Health agency - as “a generic name grouping together all the types of toxicological index that make it possible to establish a relationship between a dose and an effect. (threshold effect toxic) or between a dose and a probability of effect (toxic with no effect threshold)”

10. References

Laws

Law no. 76-629 dated 10 July 1976 on nature protection

Law no. 92-3 dated 3 January 1992 on water

Law no. 2006-1772 dated 30 December 2006 on water and aquatic environments (refers to WFD)

Regulation

Arrêté du 9 septembre 1997 relatif aux installations de stockage de déchets non dangereux.

Arrêté du 08/07/03 relatif aux critères et méthodes d'évaluation des propriétés de dangers H1 explosif, H2 comburant, H3 inflammable et facilement inflammable d'un déchet

Arrêté du 9 août 2006 relatif aux niveaux à prendre en compte lors d'une analyse de rejets dans les eaux de surface ou de sédiments marins, estuariens ou extraits de cours d'eau ou canaux relevant respectivement des rubriques 2.2.3.0, 4.1.3.0 et 3.2.1.0 de la nomenclature annexée à l'article R. 214-1 du code de l'environnement

Arrêté du 11 janvier 2007 relatif aux limites et références de qualité des eaux brutes et des eaux destinées à la consommation humaine mentionnées aux articles R. 1321-2, R. 1321-3, R. 1321-7 et R. 1321-38 du code de la santé publique

Arrêté du 30 mai 2008 fixant les prescriptions générales applicables aux opérations d'entretien de cours d'eau ou canaux soumis à autorisation ou à déclaration en application des articles L. 214-1 à L. 214-6 du code de l'environnement et relevant de la rubrique 3.2.1.0 de la nomenclature annexée au tableau de l'article R. 214-1 du code de l'environnement

Arrêté du 17 décembre 2008 établissant les critères d'évaluation et les modalités de détermination de l'état des eaux souterraines et des tendances significatives et durables de dégradation de l'état chimique des eaux souterraines

Arrêté du 23 décembre 2009 complétant l'arrêté du 9 août 2006 relatif aux niveaux à prendre en compte lors d'une analyse de rejets dans les eaux de surface ou de sédiments marins, estuariens ou extraits de cours d'eau ou canaux relevant respectivement des rubriques 2.2.3.0, 3.2.1.0 et 4.1.3.0 de la nomenclature annexée à l'article R. 214-1 du code de l'environnement

Arrêté du 25 janvier 2010 relatif aux méthodes et critères d'évaluation de l'état écologique, de l'état chimique et du potentiel écologique des eaux de surface pris en application des articles R. 212-10, R. 212-11 et R. 212-18 du code de l'environnement

Arrêté du 12 décembre 2014 relatif aux conditions d'admission des déchets inertes dans les installations relevant des rubriques 2515, 2516, 2517 et dans les installations de stockage de déchets inertes relevant de la rubrique 2760 de la nomenclature des installations classées

Arrêté du 8 février 2013 complémentaire à l'arrêté du 9 août 2006 relatif aux niveaux à prendre en compte lors d'une analyse de rejets dans les eaux de surface ou de sédiments marins, estuariens ou extraits de cours d'eau ou canaux relevant respectivement des rubriques 2.2.3.0, 3.2.1.0 et 4.1.3.0 de la nomenclature annexée à l'article R. 214-1 du code de l'environnement

Circulaire no. 2000-62 du 14 juin 2000 relative aux conditions d'utilisation du référentiel de qualité des sédiments marins ou estuariens présents en milieu naturel ou portuaire défini par l'arrêté interministériel

Circulaire du 4 juillet 2008 relative à la procédure concernant la gestion des sédiments lors de travaux ou d'opérations impliquant des dragages ou curages maritimes et fluviaux

Circulaire du 24/12/2010 relative aux précédents décrets modifiant la nomenclature des ICPE de traitement de déchets

Décret no. 2009-1341 du 29 octobre 2009 modifiant la nomenclature des installations classées

Décret no. 2010-369 du 13 avril 2010 modifiant la nomenclature des installations classées

Directive 2008/98/CE du Parlement européen et du conseil du 19 novembre 2008 relative aux déchets et abrogeant certaines directives

Directive Européenne no.96-29 du 13 mai 1996 N° 9629 EURATOM fixant les normes de base relatives à la protection sanitaire de la population et des travailleurs contre les dangers résultant des rayonnements ionisants

Directive 2000/60/CE du Parlement européen et du Conseil du 23 octobre 2000 établissant un cadre pour une politique communautaire dans le domaine de l'eau

Règlement (CE) Nº 1488/94 de la Commission du 28 juin 1994 établissant les principes d'évaluation des risques pour l'homme et pour l'environnement présenté par les substances existantes conformément au règlement (CEE) no 793/93 du Conseil

Directive 1999/31/CE du Conseil du 26 avril 1999 concernant la mise en décharge des déchets

Directive no. 2006/118/CE du 12/12/06 sur la protection des eaux souterraines contre la pollution et la détérioration

Décision no. 2003/33/CE du 19/12/02 établissant des critères et des procédures d'admission des déchets dans les décharges, conformément à l'article 16 et à l'annexe II de la directive 1999/31/CE

Standards (NF for the French version, EN standards usually available in English)

NF EN 15863 (2015-05-15) Title: Caractérisation des déchets - Essais de comportement à la lixiviation pour la caractérisation de base - Essai de lixiviation dynamique des monolithes avec renouvellement périodique du lixiviant, dans des conditions d'essai fixes.

NF EN 12457-2 (2002-12-01) Title: Caractérisation des déchets - Lixiviation - Essai de conformité pour lixiviation des déchets fragmentés et des boues - Partie 2: essai en bâchée unique avec un rapport liquide-solide de 10 l/kg et une granularité inférieure à 4 mm (sans ou avec réduction de la granularité).

NF P94-050 (1995-09-01) Title: Sols: reconnaissance et essais - Détermination de la teneur en eau pondérale des matériaux - Méthode par étuvage.

NF P94-054 (01/10/1991) Title: Sols: reconnaissance et essais - Détermination de la masse volumique des particules solides des sols - Méthode du pycnomètre à eau.

XP P94-047 (1998-12-01) Titre : Sols: reconnaissance et essais - Détermination de la teneur pondérale en matières organiques d'un matériau - Méthode par calcination.

NF P94-057 (01/05/1992) Title: Sols: reconnaissance et essais - Analyse granulométrique des sols - Méthode par sédimentation.

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NF P94-040 (1993-10-01) Titre : Sols reconnaissance et essais - Méthode simplifiée d'identification de la fraction 0/50 mm d'un matériau grenu - Détermination de la granulométrie et de la valeur de bleu.

NF EN 15169 (2007-05-01) Titre : Caractérisation des déchets - Détermination de la perte au feu des déchets, des boues et des sédiments.

XP CEN ISO/TS 17892-3 (2005-08-01) Titre : Reconnaissance et essais géotechniques - Essais de laboratoire sur les sols - Partie 3: détermination de la masse volumique des particules solides - Méthode du pycnomètre

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NF P94-068 (01/10/1998) Title: Sols: reconnaissance et essais - Mesure de la capacité d'adsorption de bleu de méthylène d'un sol ou d'un matériau rocheux - Détermination de la valeur de bleu de méthylène d'un sol ou d'un matériau rocheux par l'essai à la tâche.

NF P94-051 (1993-03-01) Sols: reconnaissance et essais - Détermination des limites d'Atterberg - Limite de liquidité à la coupelle - Limite de plasticité au rouleau.

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NF P94-093 (01/10/1999) Title: Sols: reconnaissance et essais - Détermination des références de compactage d'un matériau - Essai Proctor normal. Essai Proctor modifié.

NF P94-078 (01/05/1997) Title: Sols: reconnaissance et essais - Indice CBR après immersion. Indice CBR immédiat. Indice Portant Immédiat - Mesure sur échantillon compacté dans le moule CBR.

NF EN 15309 (2007-07-01) Caractérisation des déchets et du sol - Détermination de la composition élémentaire par fluorescence X.

NF CEN/TS 14405 (2005-07-01) Caractérisation des déchets - Essai de comportement à la lixiviation - Essai de percolation à écoulement ascendant (dans des conditions spécifiées)

NF ISO 18589-1 (2005-12-01) Title: Mesurage de la radioactivité dans l'environnement - Sol - Partie 1: lignes directrices générales et définitions

NF P11-300 (01/09/1992) Title: Exécution des terrassements - Classification des matériaux utilisables dans la construction des remblais et des couches de forme d'infrastructures routières

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