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# EARTHWORKS MANUAL

## DESIGN AND CONSTRUCTION OF EARTH-STRUCTURES

### PART 2 - SPECIFIC TECHNICAL DEVELOPMENTS

# 2B / TREATMENT OF MATERIALS

TECHNICAL COMMITTEE 4.4 "*EARTHWORKS AND UNPAVED ROADS*"
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PIARC

# ABOUT PIARC

*The World Road Association (PIARC) is a non-profit organization, founded in 1909 to improve international cooperation and to encourage progress in roads and road transport.*

*The study, which is the subject of this Manual, was defined in the PIARC Strategic Plan 2012-2015 approved by the Council of the World Road Association, whose members represent the governments of its member countries. The members of the Technical Committee responsible for this report were chosen by the governments of these countries for their particular expertise.*

*The opinions, findings, conclusions and recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of the organizations or bodies to which they belong.*

*This report is available on the website of the World Road Association (PIARC): http://www.piarc.org*



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*ISBN: 978-2-84060-643-7*

*Cover page: A89 Highway Auvergne - Excavation treatment © RAZEL (France)*

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2B / TREATMENT OF MATERIALS

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# 1. PREAMBLE

## 1.1. Development of treatment techniques

The treatment technique has been known and practiced for a long time, particularly in the United States. In Europe, its large-scale application for the construction of earthworks began in the 1960s.

Since then, the technique of soil treatment, which we are interested in in this part of the Manual, has undergone spectacular development. There are many reasons for this development.

- Evolution in the management of the material resources necessary for the project:
  - Diminishing resources of good quality materials
  - Abundance of fine soils, especially water-sensitive soils in countries with humid climates
  - Optimal use of the materials encountered on the site which constitute natural resources that can be valorised by treatment with lime and/or cement or hydraulic road binders.
- Economic arguments: seeking to reduce infrastructure construction time and costs
- Technical progress: progress in the valorization of treated materials thanks to a better characterization of their properties and an improvement in working methods, execution equipment and treatment products.
- Guaranted performance and durability.
- Environmental aspects whose importance has increased in recent years: preservation of natural resources of noble materials, reduction of transport, particularly of material transport traffic on the public network, limitation of landfill sites, to avoid the degradation of existing roads.

In addition to these reasons, there are also criteria concerning the role of each of the layers of the structure in the dimensioning of the works.

Soil treatment allows to obtain platforms with high mechanical performances.

The consideration by designers of the performance of the capping layer in the design of pavements enables projects to be optimised (design developed in France and currently being extended in Europe).

The development of soil treatment technique is dependent on the economic possibilities for the supply of lime and hydraulic binders - either from the country's own resources or from imports.

**Example of development in France**

The technique of soil treatment has been used in France since the 1960s.

Until the 1970s, it was mainly concerned with the reuse of water-sensitive and/or wet soils as backfill, particularly when carrying out major motorway programme projects.

Later, the technique was extended to the creation of capping layers, starting with the reuse of fine soils, more particularly silts, and then gradually an increasingly wide range of materials such as clayey gravels, or even mixtures of fins soils with blocky elements or natural gravels, as well as marls.

*Picture 1: Lime treatment of fill [A36 Beaune-Dôle (1980)]*

### 1.2. VECTORS OF PROGRESS IN TREATMENT TECHNIQUES

We have just underlined the important economic impact of the development of treatment techniques using lime and hydraulic binders. This methodology plays a major role in the development of the use of material resources on site.

The constant progress of these techniques is based mainly on the following components:

- the rational evolution of methodologies;
- the best knowledge of the nature and behaviour of materials, based on in-depth studies, representative tests and feedback from construction sites;
- the use of new hydraulic binders, specially adapted to the treatment of different classes of materials;
- the progress made on the equipment, in terms of mixing, dosing precision and guidance and, also, the progress made on the control of water content.

## 1.3. PERSPECTIVES

An analysis of the evolution of the technique over the last 60 years shows that soil treatment has improved and developed thanks to advances in technology. The value of the treatment has increased in response to new issues. Originally, the main aim was to reduce the cost of construction work, then to reduce energy consumption, then to preserve noble natural resources, and then to recycle surplus materials and co-products of the construction industry.

Today, we must give priority to the preservation of our global environment through a logic of sustainable development based on rational thinking and methods. In the field of works in treated soils, the choice of solutions should be confirmed or new applications should be justified, based on rigorous methods of analysis of the environmental balance.

The balance sheet is generally favourable due to the benefits we have described above.

The future prospects for soil treatment are therefore far from fixed.

## 1.4. FIELDS OF APPLICATION

The field of application related to the earthworks activity concerns the treatment, with binders, of natural soils, weak and intermediate rocks (including chalk), recycled materials and artificial materials for the execution of earthworks during the construction and maintenance of earth infrastructures.

It concerns only layer treatment for earthworks, as opposed to column treatment, for example.

The field of activity most concerned is that of road and motorway infrastructure, as well as airport, port, industrial and logistics platforms and access roads.

It should be noted that treatment techniques have also developed in the railway sector.

It should be noted that the interest of the technique can be proven whatever the size of the building site.

The techniques for carrying out soil treatments apply:

- to embankment works (embankment bodies and specific embankments),
- to parts of particular works,
- to top section of the earthworks of fills or cuttings,
- to the capping layers,
- possibly to road base layers (Sub-base in particular) made of treated soils (generally road mixtures).

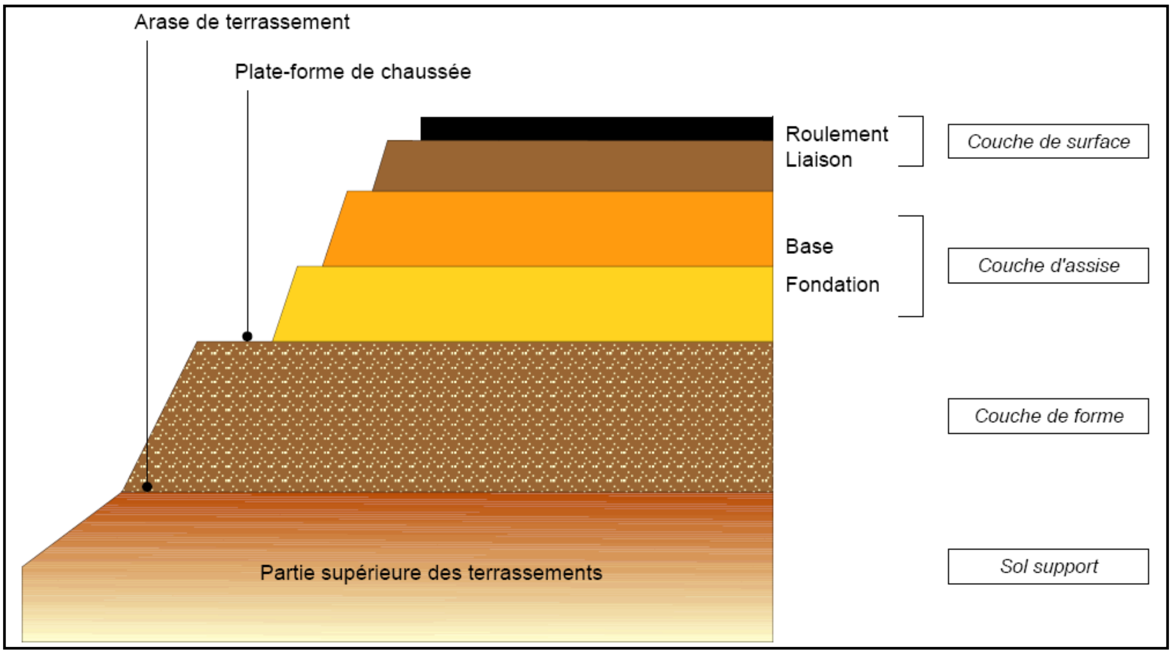



*Figure 1: Layers of the pavement structure*

## Terms and definitions pavement support

### Reference France

#### Top section of earthworks (TSE)

Upper zone of approximately one metre thickness of the soil in place (in the case of excavated profiles) or of the materials added (in the case of embankment profiles), noted TSE. It serves as a support for the capping layer or, in its absence, for the pavement layers.

#### Subformation level (or level surface of earthworks)

Upper surface of the top section of earthworks (TSE).

#### Capping layer

Layer laid over the subformation level to adapt the characteristics of the fill materials or the ground in place to the geometric, mechanical, hydraulic and thermal characteristics, taken as hypotheses in the design and calculation of the pavement dimensioning.

#### Formation level (or Pavement foundation)

Surface of the capping layer intended to receive the pavement layers. In the case where the capping layer is not present, the formation level merges with the subformation layer.

#### Pavement structure

Main structural element of a roadway. The foundation can be laid in one layer, called the base layer, or in several layers, called the base layer and sub-base layer.

## 1.5. TREATMENT REFERENCE DEFINITIONS

### 1.5.1. General Definition

The treatment of a material means the operation of mixing the material more or less completely with lime, or hydraulic binder, or both, and possibly with additional water. The aim is to improve the properties of materials with poor or insufficient characteristics for use in earthen structures.

### 1.5.2. Definitions processing operations

**Reference European Standard**

**(EN 16907 Earthworks — Part 4: Soil treatment with lime and/or hydraulic binders)**

***Soil treatment***

Definition

A general term for the process of modifying a given soil to make it suitable for its intended use. The modification is achieved by the mixing resulting from the addition of a binder or combination of binders to the soil.

The treatment includes both improvement and stabilization processes.

***Soil Improvement***

Definition

Operation aimed at improving the physical properties (in the short term) of a soil, or more generally of a material, by adding a binder.

This can affect, among other things, water content, plasticity, sensitivity to water and frost, compressibility and swelling potential.

The amount of binder added may not be sufficient to achieve significant permanent properties.

Achievement objectives

Soil improvement is carried out when the material to be laid presents difficulties in handling, placement, traffic or compaction because the water content and/or plasticity is too high. These soils can be improved by the introduction of a binder, usually lime, in the form of quicklime.

The goal is to allow the treated soil to achieve one or more of the following properties:

- the ability to be handled by conventional earth-moving machinery
- the ability to be satisfactorily compacted in layers
- trafficability and capacity to provide a working platform for the upper layer
- preparation of the material for further processing

***Soil stabilization***

Definition

Operation aimed at obtaining a homogeneous mixture of the soil with binder(s) and possibly with an addition of water, which, with appropriate compaction, significantly changes (generally in the medium or long term) the characteristics of the soil and makes it stable in particular against the action of water and frost.

Achievement objectives

The goal is to enable the treated soil to withstand one or more of the following:

- vertical, horizontal or oblique static loads
- dynamic loads
- contact with water
- frost

**Definitions (according to PIARC):**

- **Treatment:** A general term for a process of modifying a given material to perform its intended functions.
- **Improvement:** the process of improving the physical properties of a soil - such as natural water content, plasticity, sensitivity to water and frost, compactability - by adding a binder. However, the amount of binder added is insufficient to achieve a significant and lasting hardening.
- **Stabilization:** operation which consists in increasing very significantly (generally in the medium or long term) the mechanical characteristics of a soil, so as to bring it into a definitive state of stability, in particular with regard to the action of water and frost. It enables permanently measurable performance to be achieved using methods specific to solid materials.

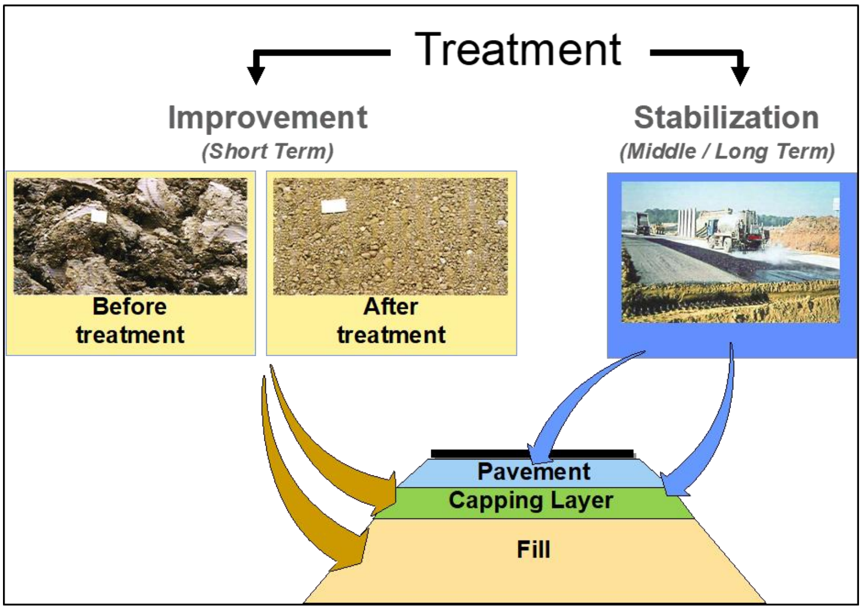



*Figure 2: Treatment operations*

#### 1.5.3. Definitions treatment products

**European Standard Reference**

***Binders***

The treatment products under consideration are limited to the following standardised products: cement, fly ash, blast furnace slag, hydraulic road binder and air lime, and are designated as binders.

***Hydraulic Binders***

Cement, fly ash, blast furnace slag and road hydraulic binder are designated as hydraulic binders.

Air lime is not a hydraulic binder, but it has a pozzolanic action.

# 2. CONSTITUENTS OF THE TREATED MATERIALS

## 2.1. MATERIALS SUITABLE FOR TREATMENT

In general, the categories of materials suitable for treatment with lime and binders are as follows:

- natural soils
- weak and intermediate soft rocks (including chalk)
- recycled materials
- artificial materials / industrial by-products

They may also consist of mixtures of these different categories.

- marginal materials

More generally, after specific study, some marginal materials (soil or rock) may be suitable for treatment for reuse.

*NOTE: Some types of materials can be pre-treated, for example with lime, to adjust the water content and/or to flocculate the clay.*

They must comply with the following:

- Dmax must be compatible with the performance of the equipment (mixer, roller, grader, etc.) as well as the geometrical requirements, in particular with regard to the thickness of the layers after compaction;
- no constituent in a proportion that would adversely affect the setting, hardening, performance and volumetric stability of the treated material.

The materials are identified according to the classifications applicable in the countries concerned and in application of specific standards where appropriate.

### 2.1.1. Natural soils

**Definition:** A natural material is derived from the weathering of source rocks.

We use soil classes as a basis. They can be defined as follows:

- A - fine soils
- B - sandy and gravelly soils with fines
- C - soils with fine and coarse elements
- D - water-insensitive soils

Treatment is indicated for most Class A, B and C soils under certain conditions.

For soils with large elements, the parameter Dmax is to be considered. It must be compatible with the performance of the equipment as well as the geometric requirements, in particular as regards the thickness of the layers after compaction. This may lead to the removal of large elements before treatment.

Soils that are insensitive to water can be treated with hydraulic binders for use as a sub-base layer, provided an appropriate grain size corrector (ash, filler) is applied.

### 2.1.2. Rocks

***Soft and intermediate rocks (including chalk)***

At this stage, treatment of these rock classes may be considered where they constitute the potential resources of the project site. In this case, the treatment must be the subject of specific in-depth studies. First of all, the suitability of the rocks for splitting by means of the equipment available on the construction site should be checked.

Particular care must be taken when in presence of compact rocks of an evolutive nature. Experiments in this area are carried out on a case-by-case basis.

***Special case of chalk***

With regard to the use of treated chalk, we draw attention to the variable nature and behaviour of these materials and their high sensitivity to variations in water content.

Mixing the chalk with the binders is delicate; parts of untreated layers may remain, not always detectable by the controls carried out. Care must be taken to ensure the quality of these operations, as mixing defects allow run-off water to penetrate and cause disorders in the stability of the backfill or the capping layer.

References to specific guides and feedback can be consulted in Europe, particularly in the UK and France.

***Examples of rocks used as backfill or as a capping layer after treatment:***

- pelites, clayey rocks formed by the erosion of the primary bases
- mollasses, Tertiary or Quaternary rocks
- marls
- shale, which is particularly delicate to treat due to the presence of flaky minerals (micas, for example) which prevent the hardening of the treated material
- chalks that require special processing techniques

**PIARC Reference:** Case studies in PIARC Technical Report 2012 (See booklet “2A.I - Marginal materials” of the Earthworks Manual).

### 2.1.3. Special cases of organic soils

These are natural materials containing organic matter.

Examples: vegetal earth, forest humus, vases, peat,...

These materials are most often reserved for slope coverings or landscape earth mound barriers.

The suitability of these materials depends on the characteristic parameter, the organic content: **% MO** and the geotechnical behaviour.

Materials are generally considered to be:

- Low organic for threshold values **3 ≤ % MO ≤10**
- Highly organic for threshold values **% MO ≥ 10**

It is not recommended to use highly organic materials (forest humus, peat...).

The possibility of using materials with low organic content (vegetal earth,...), in particular as backfill or landscape fill, can be considered with an appropriate lime treatment, subject to a specific in-depth study.

**PIARC Reference:** Feedback Airport in Germany (See booklet “2A / Materials” of the Earthworks Manual).

### 2.1.4. Artificial materials (Alternative materials)

***Definitions:***

**Reference PIARC Technical Report 2007**

Artificial materials result from industrial processes involving thermal or other modification (such as fly ash, bottom ash, etc.). They are generally referred to as industrial by-products. They are not necessarily chemically inert.

## New reference

The designation " **Alternative Materials**" is more appropriate and is the subject of a new PIARC definition (See booklet “2A / Materials” of the Earthworks Manual).

Industrial by-products can be:

- Either materials suitable for treatment
- Either binders or components of binders used in the process.

For some, like fly ash, they can have both functions.

***Use of industrial by-products as material constituents***

Many projects are carried out using and valorising the industrial waste resources of the region concerned.

However, feedback should be sufficient to advise on the use of these materials.

These include the following by-products:

- First of all, the **silico-aluminous fly ash**. They come from the combustion of coal in thermal power stations.

Note that the compaction of the treated ash is technically difficult to be obtained (concentration of "balls" resulting in a fluage phenomenon).

*Picture 2: Capping layer made of treated fly ash*

**Feedback References** (See Booklet “2A.III - Alternative Materials” of the Earthworks Manual)

- **Non-hazardous waste incineration slag** which must be the subject of specific user guides and comply with important regulations related in particular to environmental aspects.

Example: France Guide CEREMA MIDND

**Feedback References** (See Booklet “2A.III - Alternative Materials” of the Earthworks Manual)

*Picture 3: Creation of a gravel capping layer from recycled non-hazardous waste incineration slag*

- **Coal shales** which are sterile materials deposited at coal mine sites. We can distinguish:
  - red shales (burnt) usable, without treatment, as backfill or as a capping layer;
  - black shales which can be used, possibly, after treatment, mainly as backfill, for the construction of roads and industrial platforms.

Example: construction in 2002 of the Dourges platform (France) (*) using black shale treated with hydraulic road binders.

**Reference: PIARC Technical Report 2012R37FR**

*Picture 4: Treatment of coal shale with hydraulic road binder*
*(Dourges logistics platform Delta 3 (2002))*

The experience of the construction sites carried out shows that the use of these materials is always delicate. Checks on the suitability of these materials for processing must focus, as a matter of priority, on the sulphur and organic matter content.

- **Potash Mine Tailings**. The same caution as that recommended for clayey and evolutive rocks should be observed. Suitability for treatment must be verified on a case-by-case basis and specific studies will be carried-out.

***Recycled materials***

Recycled materials come from the demolition of buildings or infrastructures, or from excavations. They are normally chemically inert.

**Feedback References** (See Booklet "2A.III - Alternative Materials" of the Earthworks Manual)

## 2.2. PARAMETERS TO BE TAKEN INTO ACCOUNT IN TREATMENTS

We mainly quote those concerning soils. There are generally three types of parameters from identification that are considered to be representative with respect to treatment.

### 2.2.1. Parameters characterizing the nature of soils

- Argilosity

  It is expressed by one of the following values:

  - the plasticity index (**PI**)
  - the methylene blue value (**VBS**)

  Argilosity is a key factor in the choice of treatment product and determines whether or not it is necessary to carry out a pre-treatment with lime in the case of a double treatment.

  It should be noted that lime is the most suitable for the treatment of materials with a high content of clay (backfill and Top Section of the Earthworks (TSE), or even capping layers).

- Granularity (particle size distribution)

  It is determined by particle size analysis and more particularly by:

  - the value of **Dmax**, the dimension of the largest elements in the soil
  - the passing **at 0,08 mm** (fines content)

- Content of chemical components such as:

  - organic matter
  - phosphates and nitrates
  - chlorides
  - sulphates and sulphides, which are most frequently found in soils (gypsum in particular)

  The contents of chemical components are to be taken into account as the suitability for treatment requires that certain thresholds for the content of these constituents are not exceeded. They have complex adverse effects on the hydraulic setting and hardening and can initiate disorders, for example as a result of **swelling phenomena**, which will occur during operation of the structure.

### 2.2.2. State parameters

- Moisture condition

  The moisture condition is very important for the entire treatment workflow. It affects on the choice of treatment products, their dosage, their setting and hardening and the conditions of use.

  It is determined by one of the following values:

  - the **$W_{NAT}/W_{OPN}$** ratio for "very dry" to "medium" states
  - the immediate bearing index **IPI**, for "wet" and "very wet" states
  - the consistency index **($I_c$)**:

$$I_c = \frac{W_L - W_{NAT}}{W_L - W_P}$$

$W_{NAT}$: natural water content,

$W_{OPN}$: Normal Optimum Proctor moisture content,

$W_L$ and $W_P$: Alterberg limits, limits which separate the liquid state from the plastic state (WL) and the plastic state from the solid state ($W_P$).

The **$I_c$** index is applicable to all water states in very clayey soils.

### 2.2.3. Behavioural parameters

- Fragmentability and degradability of coarse elements

  D > 50 mm applicable to evolutive rock materials.

**Reference** test methods France and Europe

- Abrasivity of the grain fraction (elements > 0,08 mm)

  This characteristic affects the wear of the mixing tools.

To remember:

**Main identification parameters vis-à-vis the treatment:**

- granularity: D (mm)
- argilosity: VBS - Ip
- water status: water content
- contents of chemical elements: MO - sulphates - nitrates ...
- physical characteristics: hardness – abrasiveness

## 2.3. TREATMENT PRODUCTS

As a preamble:

**REFERENCE AIPCR / TECHNICAL REPORT (2007): "PROMOTING THE OPTIMAL USE OF LOCAL MATERIALS"**

General information on the use of lime and binders

Cement and lime are still the most widely used treatment products in the world. However, treatment products are appearing that are increasingly adapted to the specific characteristics of a given material, thus increasing the number and type of materials that can be treated. Many industrial by-products can be treated and some can even be used as binders.

Among the advances are the following:

- the use of lime and hydraulic road binders with a low dust emission rate, which makes it possible to envisage treatment in sensitive urban, peri-urban and agricultural areas, in environmentally protected areas or areas at specific risk;
- the development of hydraulic road binders with adaptable mixtures (lime, slag, clinker, fly ash, etc.) for the treatment of¬ specific soils¬ or the treatment of industrial by-products;
- the use of quick-setting hydraulic road binders to reduce the waiting time before putting into circulation and to ensure faster protection against potential meteorological risks (erosion, frost, etc.);
- the increasing use in some countries of treatment products derived from industrial by-products such as over-limed steel mill slag fines for example.

### 2.3.1. Characteristics of treatment products

***Air lime***

***First of all, we briefly recall the manufacturing process of air lime.***

- **Lime manufacture**

Air lime is obtained by decarbonation of limestone (CaCO3) at a temperature of about 900 ˚C according to the reaction:

$$CaCO_3 \rightarrow CaO + CO_2 \quad \Delta H = 178 \text{ kJ/mol}$$

This reaction is reversible. The lime produced can, after hydration, slowly recarbonate in a humid environment, under the effect of carbon dioxide CO2 present in the atmosphere.

A setting is carried out in the air, hence the term "air lime", which differs from "hydraulic lime".

- **Characteristics of air lime**

The most important characteristics for the material treatment process are the following:

- the form in which air lime is used:
  - quicklime (the most commonly used),
  - slaked lime,
  - milk of lime,
  - Also note the low-dust quicklime.

    This lime is less volatile and therefore its use reduces dust emissions. Its use is recommended in certain infrastructure contracts that include special environmental protection provisions;
- the available lime content, expressed as CaO
- granularity
- the reactivity determined by a test representative of the qualities of the lime: burning, fineness of grinding and available lime content.

**References Europe:**

**EN 459-1:** Building lime

**EN 459-2:** Test methods

The most commonly used form of material processing is quicklime delivered in bulk (in bags when this is not possible).

Below are some comments on the other forms and their possible uses.

- **Slaked lime (or hydrated lime)**

As this lime is already hydrated, it does not fix water and therefore hardly reduces the water content of the soil. It is used in some countries for the neutralization of clays and the stabilization of soils with low water content. Water may need to be added to ensure optimum water content for manufacturing and processing.

- **Milk of lime (or lime slurry)**

Milk of lime is a suspension of hydrated lime in water. This form provides both the lime and the water needed to stabilize dry clay soils. The use of milk of lime is particularly suitable in dry climatic periods. In particular, it is used intensively in the southern states of the United States (especially Texas) for the stabilization of clayey soils in the top soil of earthworks and capping layer.

***Hydraulic binders***

Dan In treatment operations, cements or hydraulic road binders (HRB) are used.

- **Cements**

Cements are hydraulic binders whose characteristics comply with standards established, for the most part over many years, on the basis of extensive experience. This provides a significant guarantee of their properties and homogeneity.

The most commonly used cements are CEM II 32.5 cements (according to the European standard EN 197-1) especially for sandy loamy-clay soils and slag-based cements for chalk in particular.

**Reference Europe**

It should be noted that within the framework of the European Commission for Standardization (CEN) own marking, the cement must comply with EN 197-1 and a designation is in force (CEM I, II, III and IV).

- **Hydraulic road binders (HRB)**

For several years now, hydraulic road binders have been developed by producers (in Europe, notably France and Germany) and manufactured for specific soil treatment uses, i.e. the realization of Top Section of the Earthworks (TSE), water-insensitive backfill bases and capping layers.

To use HRB, it is advisable to refer to a standard that gives the composition, specifications and compliance criteria of these binders. (For example, in Europe EN 13282 - parts 1 and 2)

The advantages of this type of binder, compared to conventional cements, are of several kinds. We will highlight them below (§ 3.3.1).

The lime content of these binders is variable depending on the desired effect; it can be suffisante to avoid pre-treatment with quicklime in the case of embankment bases or TSE - this is not the case for capping layers.

Continuous research and targeted studies are carried out by manufacturers to further improve the characteristics of these products.

**Reference Europe**

Hydraulic road binders comply with EN 13282-1 or EN 13282-2.

***Industrial by-product binders***

The use of these binders is generally intended as constituents in road mixtures.

**References Europe**

- **Fly ash**

In Europe, fly ash shall be either silica fly ash in accordance with EN 450-1, or calcareous fly ash in accordance with EN 14227-4.

Note that silica fly ash is a pozzolanic material and requires a source of calcium oxide available from lime or cement to produce a hydraulic reaction.

- **Slag**

In Europe, blast furnace slag must comply with EN 15167-1, or for granulated blast furnace slag to EN 14227-2.

Note that other constituents are normally required to improve the hydraulic reactivity of the slag.

#### 2.3.2. Other types of binders

Other types of binders based on polymers, fibres,... are used in some countries. Their characteristics are to be considered on a case-by-case basis.

### 2.4. Water

The water content in the soil and the nature of the water are decisive criteria for the success of the treatment operation.

Water should not adversely affect the processing, hardening and performance of the mixture. It is advisable to recommend in contracts a water analysis and to refer to compliance in the appropriate category (practically potable water).

It should be noted that the possible presence of certain ions (such as H+, SO3 or NO3 for example, in the free water retained in the soil) can alter the action of the treatment products. The nature of the water may be the subject of a standard.

**Example France:** NF P98-100 type 1 (or possibly type 2 after specific study).

## 3. TREATMENT TECHNIQUES

### 3.1. Field of application

Soil treatment techniques are based on the properties and actions of the binders used:

- Quicklime
- Hydraulic binders
- Possibly other types of binders that would require validation through testing.

We limit ourselves here to products, quicklime and hydraulic binders, which are generally well identified by standards or product data sheets.

Other products will be covered in the Unpaved Roads section of the manual.

The treatment techniques can be used on different parts of the earthworks or different structuring layers, which we describe below:

- Embankment core (current embankment)
- Parts of specific embankments
    - High embankment bases
    - Carapace (Shoulder) and Fill Core
    - Fill spades
    - Embankment bases in flood-prone areas (FA) and wetland areas (WA)
    - Embankments adjacent to structures (technical blocks): bridges, hydraulic structures, culvert, hydraulic path, ...
    - Retaining structure (reinforced earth, ...)
    - Unloading docks
- Parts of specific cuts
    - Slope stiffening, particularly due to limited right-of-way
    - Protection of cuts slopes (Masks)
- Structuring layers
    - TSE in excavation or embankment
    - Capping layer
    - Pavement structure, usually foundation layer

## Reference European Earthworks Standard

**Parts of an infrastructure fill: general case**

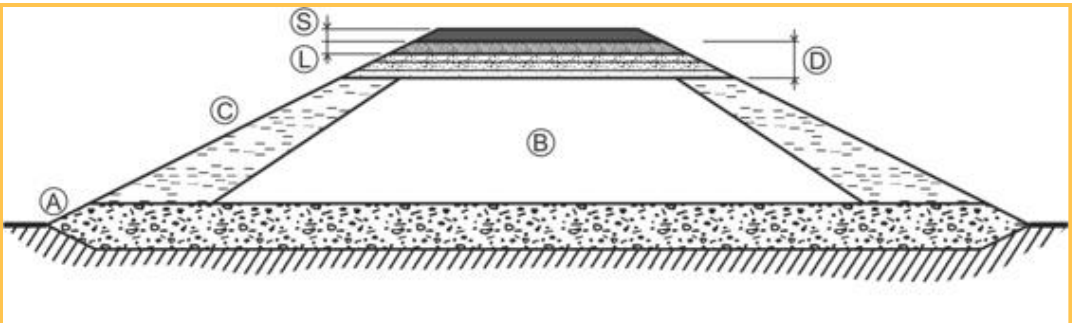



*Figure 3: Type of fill*

**Legende**

| | | | |
|---|---|---|---|
| A — | base | D — | upper zone |
| B — | core | L — | capping layer (part of the upper zone) |
| C — | shoulders | S — | superstructure (pavement/rail track) |

*Picture 5: Embankments adjacent to the works (RN 88 LE PUY – Crédit RAZEL)*

*Picture 5 bis: Example of use of lime treated materials as embankment behind a structure (Copyright Guide Matériaux chaulés)*

*Picture 6: Masks Lot 22 TGV East (chalk treated with 7% HRB)*

*Picture 7: Masks Lot 22 TGV East (chalk treated with 7% HRB)*

## 3.2. PROPERTIES / ACTIONS OF QUICKLIME TREATMENT

As a preamble, we recall that a test method is recommended to quantitatively characterize, at the study stage of a project, the conditions defining a fine wet soil,

We can refer mainly to the **immediate bearing index (IPI)** of the soil measured at its natural water content on a test specimen compacted with "Normal Proctor" energy (Reference France and Europe).

### 3.2.1. Actions of quicklime

Quicklime has several types of action on the treated soil, which we recall below.

- Immediate actions (produced at the time of mixing):
  - reduction of the natural water content;
  - modification of the characteristics of the clay fraction of the soil.

- Long-term actions (continued over several months):
    - pozzolanic action;
    - syntaxic action.
- Neutralization of the acidity of the environment

It should also be noted that the addition of lime to the soil increases the pH of the soil very quickly and significantly, above 12, which is an important factor in hydraulic setting.

### 3.2.2. Decrease in natural water content

During the mixing of lime and material, three phenomena occur:

- the hydration of quicklime, which results in the reaction:

$$\mathbf{CaO + H_2O \Rightarrow Ca(OH)_2 \ \Delta H = -62{,}8\ kJ/mol}$$

- The heat released by this reaction (64.8 kJ/mol) causes a certain amount of water to vaporize;
- the production of hydrated lime increases the mass of solids in the mixture.

These three phenomena contribute to the lowering of the natural water content of the materials.

Lime treatment is particularly indicated for materials whose moisture state is between "wet" and "very wet".

In practice, as an indication, **the order of magnitude observed** for the action of quicklime varies from:

**1 % to 3 % decrease in water content per percent (1%) lime dosage**

### 3.2.3. Modification of the clay fraction of the material

Quicklime acts on the electric charges of the fine particles and produces their floculation. This action modifies certain geotechnical characteristics of the material, first of all it causes the reduction of the plasticity index (**PI**). At the same time, it increases the shear strength and modifies the compaction characteristics of the material.

An illustration of these phenomena, the immediate actions of lime on clayey soils, is given by the following figures taken from the GTS Guide applied in France.

**Reference France:** Soil treatment guide

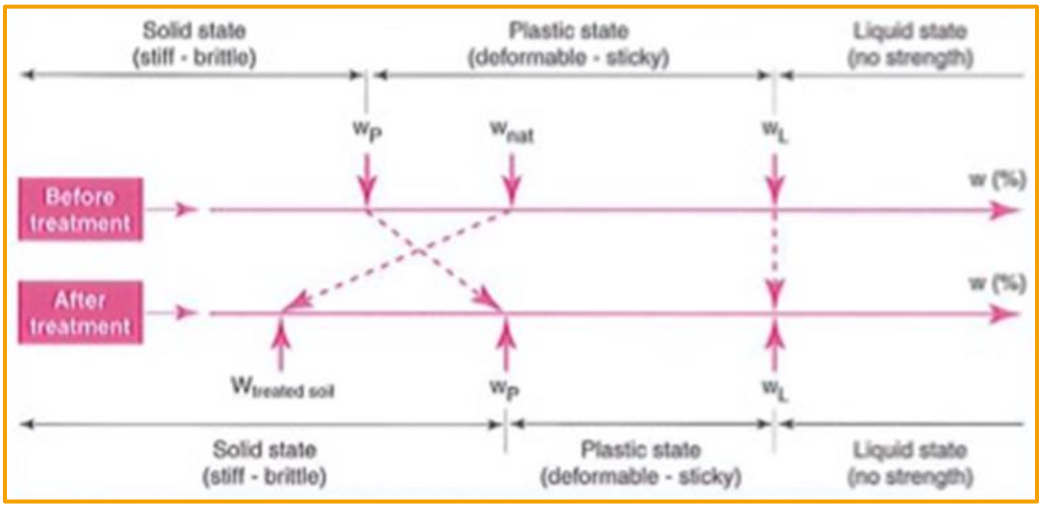



*Figure 4: Immediate change in the behaviour of a wet clay soil created by the introduction of quicklime*

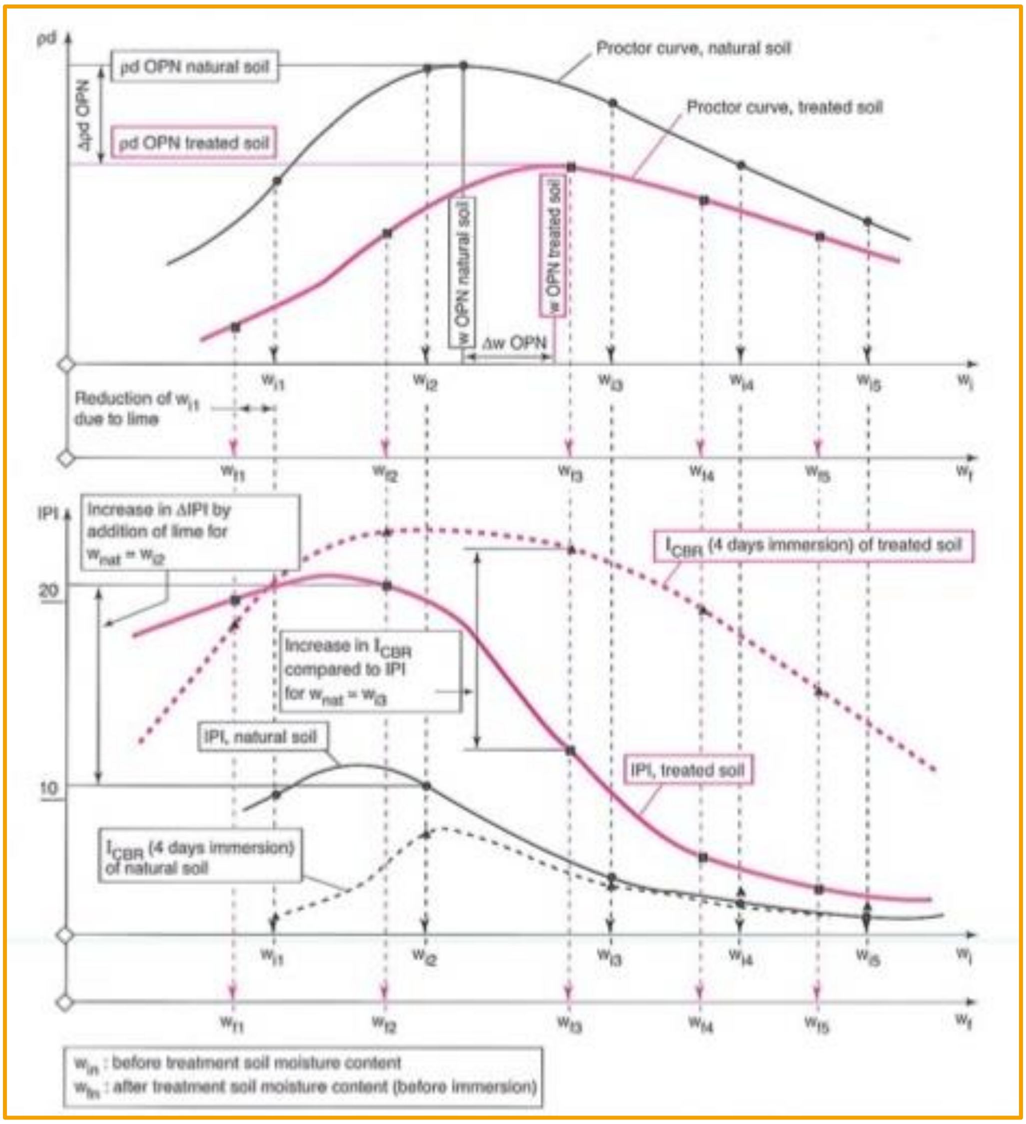



*Figure 5: Representation of the effects of lime on the compaction and shear strength characteristics in the case of a medium clay soil(*) (PI between 12 and 25) treated with 2% quicklime - (*) Soil class A2 according to the French classification*

### 3.2.4. Pozzolanic action

The addition of lime to soils containing clay elements results in the precipitation and crystallization of alumina ferrosilicates.

The factors involved in the hydraulic setting of the mixtures are the temperature of the surrounding, the quantity and nature of the clay fraction, and the moisture state of the soil.

The pozzolanic action significantly improves the mechanical characteristics of the treated materials, especially their insensitivity to water.

Water insensitivity can be characterized by the vérification of:

$$I_{CBR} / IPI \geq 1$$

**Reference Europe**

### 3.2.5. Syntaxic action

This action occurs when lime is incorporated into carbonated materials (limestone, chalk) and is characterised by the phenomenon of air setting which durably improves the characteristics of the materials thus treated and can allow their use as backfill or in Tops Section of the Earthworks (TSE).

### 3.2.6. Use of lime treatments

Lime is mainly used for soil improvement, as defined in paragraph 1, to achieve the following objectives:

- **Lowering the water content**

To ensure better trafficability and to allow the materials to be processed under optimal acceptable conditions.

The treatment applies mainly to materials used in common embankment bodies.

- **Water desensitization**

Water desensitization can be achieved when lime treatment is carried out on materials of low to medium clay content (sufficient but not in excess).

**Reference GTR France:**

- clayey soils (silt, sand, clay) of classes A1, A2 or even A3
- sands and clayey gravel of classes B5, B6
- granular materials of classes C1, C2 with a minimum VBS of 0,5

Before considering the improvement of mechanical characteristics, this objective may be sufficient for the materials constituting certain parts of structures, particularly the bases of embankments in wet or flood-prone areas.

This type of treatment may be suitable for forming technical blocks or TSE with a certain level of load-bearing capacity.

**Example GTR France (TSE n°2 or 3 according to arase).**

It can also be considered for capping layers, if the required bearing capacity is achieved and under low frost depth conditions.

- **Improvement of mechanical characteristics**

Notably:

  - for embankment bodies, where the materials are:
    - of an evolutive nature, such as, **for example, marls, those of class R31 to R34 according to the French GTR**, in particular with regard to long-term deformations and evolutions,
    - erodible soils such as predominantly sandy soils on the slopes of cuttings and embankments

**USA reference:** use of lime in the form of milk of lime to improve the mechanical characteristics of dry or very dry clay soils

  - in high embankment bases (H > 10 m)
  - in embankments bases located in wet or flood-prone areas, or technical blocks where improvement of mechanical characteristics is required
  - for stiffening slopes, especially where rights-of-way are limited or access is difficult
  - for the improvement and upgrading of TSE
  - possibly, for capping layers.

On the other hand, the action of the lime, which causes the clay floculation can allow double treatments [lime-cement, lime-hydraulic road binders (HRB)], double treatments that also facilitate the material flow into a treatment plant for lime pre-treated soils, when this type of mixing has been chosen.

## 3.3. Properties / actions of treatment with hydraulic binders

### 3.3.1. Types of hydraulic binders

Refer to paragraph 2.3.

The hydraulic binders to be considered are essentially:

- cements, the most widely used in a majority of countries in the world.
- hydraulic road binders, the manufacture of which is developing in Europe, particularly in France and Germany.

### 3.3.2. Action of hydraulic binders

Cements and hydraulic road binders (HRB) give the treated materials, in the presence of water, a permanent cohesion called "hydraulic setting", whose importance and quality depend on:

- the nature of the treated material;
- the type of binder used;
- the amount of binder introduced into the mixture;
- the quantity of water required to hydrate the binder;
- the quality of the grinding of the material after treatment;
- the compactness achieved during implementation;
- the temperature of the surroundings and the age of the mixture.

The role of hydraulic binders is to improve the mechanical characteristics of treated soil mixtures (binders alone or combined with lime) in a perennial way.

The characteristics of cements and those of HRB are generally defined in standards.

### 3.3.3. Cement treatments

Cement treatments are still widespread throughout the world.

#### Reference France

In materials treatment, common cements were mainly used until the 1980s. Subsequently, they were gradually replaced in some countries (particularly in Europe) by special road binders, which are more appropriate to the conditions and requirements for the use of materials in earthworks and capping layers.

### 3.3.4. Treatments with hydraulic road binders (HRB)

***Interest of HRB***

The manufacture of HRB has developed strongly since the 1980s and, since the 1990s, its use has become much more common than that of cements due to the following notable benefits:

- the constant improvement of their characteristics, which is increasingly reflected in the standardisation of many of these products;
- the achievement in the medium and long term of mechanical characteristics comparable to those obtained with conventional cements;
- a better adaptation to the specific cases of the materials to be treated, to the particularity of the building sites. For example, there are special binders for chalk;
- their longer workability period, thanks to a slower setting, and therefore a more flexible use than that of cements, during processing operations;

- the least cracking of treated materials and overlying structures (pavements, industrial platforms, etc.), due to their generally lower modulus of elasticity than that obtained by treating soils with traditional cements;
- an often more economical cost.

### 3.3.5. Use of treatments with hydraulic binders

Treatments with hydraulic binders are mainly used for soil stabilisation, as defined in paragraph 1.5.

They apply in particular to pavement structuring layers.

Obtaining the mechanical characteristics targeted by the action of the treatment with hydraulic binders allows the use of the treated materials constituting:

- TSE: with, among other things, the possibility of upgrading the classes of subformation level (or level surface of earthworks);
- the capping layer, taking into account the same criteria as those set out above for TSE;
- the sub-base layer.

The mechanical characteristics obtained on these layers can be used to help optimising the design of pavements.

Treatments with hydraulic binders are also used for specific earthworks such as:

- technical blocks and retaining blocks (e.g. weight masks);
- backfill bases made insensitive to water.

Note: "weight masks", retaining embankments by substitution or addition of added materials (natural or treated) generally implemented in an excavated area affected or likely to be affected by a landslide.

### 3.3.6. Double treatments lime - hydraulic binders

This type of treatment is mainly used for the production of capping layers, sometimes for the production of TSE.

The double treatment operation includes a lime pre-treatment of the materials, carried out before treatment with hydraulic binders. It is applied to clayey materials, for which it is necessary, first of all, to flocculate the clay fraction by the action of quicklime, to then promote setting with the hydraulic binder, more rarely to lower the water content of the material beforehand.

When the technique used is that of a treatment with hydraulic binders in the mixing plant, pre-treatment with lime is also applied to facilitate the flow of material into the feed hopper.

**PIARC REFERENCE (See Appendix 1)**

**TECHNICAL REPORT 2007:** "Promoting the Optimal Use of Local Materials"

Treatment techniques and methods

**UNITED STATES REFERENCE (See Appendix 2)**

National Lime Association October 2006 article: Mixture design and Testing Procedures for Lime Stabilized Soil

An article in the October 2006 issue of the "National Lime Association" illustrated the potential of lime treatment, not only to lower water content or improve certain soils, but also to achieve long-term stabilization.

**Article in Appendix.**

## 4. TREATMENT EQUIPMENT

**REFERENCE AIPCR**

**AIPCR TECHNICAL REPORT 2007: "PROMOTING THE OPTIMAL USE OF LOCAL MATERIALS**

**THE EQUIPMENT**

**General**

Significant technical progress has been made in the field of high-performance equipment for spreading binders, mixing and compacting treated layers. In recent years, high-performance equipment has also appeared for detecting weak areas during work or for checking that the required performance is achieved at the end of the work. Examples include the development of:

- high-powered soil pulvimixers. They enable finer grindings to be obtained, depths of action reaching or even exceeding 50 cm as well as operations on bigger stones dimensions in the soils (> 200 mm).
- speed-dependent metering spreaders with variable spreading widths and very low coefficients of variation. They guarantee a saving in binding, a better regularity of distribution of the products and thus reduce the risks of over or underdosing;
- sprinkler-buriers which greatly improve the kinetics and homogeneity of hydration of the materials and reduce water losses. The performances obtained are much higher than those of traditional surface watering equipment;
- block pulverizers whose role is to fractionate the large siliceous elements present, for example, in flinty clay formations. They thus contribute to the adaptation of the treatment to very heterogeneous soils;
- screening and mixing buckets adapted to the treatment of very small sites such as backfilling of sewer trenches or roads and mains;
- finally, integrated mobile treatment plants that allow for spot treatments on small sites and the recovery of surplus earthmoving materials or other recycled materials.

Binding agents can be applied either dry or wet with high precision, allowing specifications with tight tolerances and generating savings for the same quality.

Soil humidification by injection and burial allows high flow rates with a great homogeneity of water distribution, which is difficult to ensure due to runoff from "surface" humidification equipment.

Feedback from large projects involving the treatment of capping layers or base courses with hydraulic binders shows that in-place treatments with modern means now achieve performances very close to those obtained with in-plant treatments and make it a viable option with a slight oversize in thickness.

The orientation given to the recovery of heterogeneous materials and construction site waste has also led to significant technological developments in fixed or mobile treatment facilities, or in equipment adaptable to construction site machines. In the case of recycling platforms, the processed materials are beginning to be accompanied by an identification data sheet identifying their range of geotechnical characteristics, which makes it possible to better identify potential uses.

It is likely that this progress will continue, and overall will allow for optimized management of resources. Attention must be paid to on-site traceability of the treatment operations, which is able to better guarantee the durability of the works thus carried out.

The following is an overview of the treatment equipment resulting from the most recent information.

### 4.1. TREATMENT WORKSHOP

The choice of the whole treatment workshop will be established according to the work to be carried out, the nature of the materials, the treatment products and the conditions of the site.

We present below the different types of equipment used in the kinematics of the treatment:

- storage,
- spreading,
- mixing,
- watering and compacting.

This equipment is in constant evolution. This development meets new accuracy criteria (binder dosing, layer thickness, etc.), reliabilty and increased safety and environmental requirements (in particular dust reduction).

### 4.2. BINDER STORAGE EQUIPMENT

The treatment products are almost exclusively in powder form. Construction sites are generally supplied with binders delivered in bulk to the site by road transport, pneumatic tanker trucks or towed silos.

They're stored:

- in mobile silos, adapted to the in place treatment sites
- in stationary and vertical silos, in the case of in plant treatment.

The silos have capacities ranging from 20 to 100 t.

For some construction sites, which are small in size or difficult to access, it may be necessary to deliver the binder in bags, which must obviously be stored away from water.

This method has become exceptional in Europe. It remains common in many other countries, particularly in Africa.

Specialised transport equipment allows loading and unloading of the hydraulic binder in the best conditions (no dust emission, no risk of pollution).

*Mobile silos*

*Crédit CIMBETON*

*Fixed silos*

*Crédit CIMBETON*

*Picture 8: Silos*

### 4.3. SOIL PREPARATION EQUIPMENT

Prior to mixing with the binder, some materials may require special conditioning.

The main cases that may arise are as follows:

- extremely cohesive soils, requiring prior scarification;
- soils containing large elements exceeding 100 mm in Dmax, requiring screening or even subsequent crushing (this is mainly the case for capping layers)
- heterogeneous soils, justifying a method to reduce their heterogeneity (capping layers)
- soil too dry, requiring prior watering.

*Picture 9: Stone crusher on a tractor (RAZEL)*


*Picture 10: Mobile crusher (GTM)*

The equipment necessary for the preparation of the soil are not specific to the treatment, whose possible use is described in the section "techniques of realization".

## 4.4. Spreading equipment

### 4.4.1. Different types of spreaders

In the general case of the use of bulk powdered binders and in-situ treatment, specific spreading equipment is used.

Until the 1980s, the first generation of spreaders were volumetric metering machines. The second generation that followed also included spreaders with volumetric metering devices, but controlled by travel speed.

The latest generation of spreaders have the same tools and, in addition, are equipped with the possibility of adjusting the binder quantities by means of weighting devices. Weighing the binding agent during travel provides precise information on the spread quantity per unit area, which considerably simplifies monitoring and adjustment.

It should also be noted that equipment with variable spreading widths has recently been introduced.

On small construction sites where the binding agent is supplied in bags, no spreading equipment is used. The bags are arranged according to a predetermined geometric grid, emptied into heaps and the binder is then spread with the grader.

*Picture 11: Bag spreading (Photo CIMBETON)*

<table>
<tr><td>Different types of spreaders</td><td>First generation spreader.<br>Unit surface bulk variation of spread additive is controlled by the forward speed of the vehicle.</td><td></td></tr>
<tr><td colspan="2"></td><td></td></tr>
<tr><td colspan="2">Second generation spreader in which delivery (by volume) is interlocked with forward speed of vehicle.</td><td>Third generation spreader with delivery (by volume) interlocked with forward speed and adjusted by means of a weigher device.</td></tr>
</table>

*Picture 12: Different types of spreaders (Reference GTS)*

*photo DTP Terrassement*


*photo Techniques de l'Ingénieur*


*photo CIMBETON*

*Picture 12 bis: Different types of spreaders*

### 4.4.2. Spreading accuracy

The quantity of binding agent to be spread per unit area Q (in kg/m2 ) is given by the following relationship:

$$Q = e \times \rho_d \times d / (100 - d)$$

- d is the target binder dosage (mass of binder on mass of dry soil, in %),
- e is the thickness of the soil layer in place to be treated
- $\rho_d$ is the dry density on the ground just prior to treatment (in kg/m3).

Spreading accuracy is determined by two factors, accuracy and variation. Accuracy is the observed difference between the average weight of binder actually applied and the target weight per unit area. The coefficient of variation Cv is expressed as follows (in %):

$$Cv = 100 \times s / m$$

- where s is the standard deviation calculated on a population of representative measurements and m is the mean.

Of course, other factors influence the quality of spreading: general design of the machine (including its ability to move smoothly), design and performance of the metering system, driving aids, ergonomics of the operator's platform, control and tracking systems.

## 4.5. Mixing

Mixing of the materials with the binders can be done either in place or in a mixing plant.

### 4.5.1. In-place mixing equipment / Mixers

The mixers are of different types. We can distinguish:

- the rotospades;
- mixers with fixed or animated tools.

***Rotospades***

The use of this equipment is nowadays limited to small treatment sites with difficult access.

These are machines from the agricultural field, adapted according to the needs in the field of "Civil Engineering".

Rotospades are towed materials with a mixing depth of between 25 and 35 cm. These materials are particularly suitable for the treatment of very cohesive and humid soils, as well as for narrow construction sites (road widening for example).

*Picture 13: Rotospade*

***Stationary tools mixers***

Mixers of this type are reserved for the treatment of soils with quicklime for use in embankment bodies, excluding the spécifiques areas (TSP, base and shell of embankment, etc.).

These materials are mainly used for:

- relatively "coarse" treatments of soil for embankment bodies, including materials containing blocks
- lime pre-treatments of very wet clay soils.

The different types of machinery suitable for these operations are as follows.

These are:

- Disc ploughs

  This equipment, usually towed by bulldozers, has two rows of discs and is capable of working materials containing blocks up to 250 mm. However, their depth of action is limited and hardly exceeds 20 cm, which increasingly limits their use nowadays.

5 t disk plough, width 2.5m, mix depth 0.15 metre approx.

Detail of mixing action produced by disk plough

*Picture 14: Disc ploughs (Reference GTR)*

*Picture 14 bis: Disc plough (Photo VINCI Construction Terrassement)*

- Blades ploughs

This equipment, which is also towed by more powerful bulldozers, reaches a much greater mixing depth of up to 50 cm. These ploughs can operate in materials containing blocks up to about 350 mm.

Detail of mixing action produced by blades ploughs

### GTR Reference

For backfill bodies, disc ploughs or blades ploughs are widely used. There are two main reasons for this:

- hitched to a powerful tractor on tracks, they are able to operate in very poor soils;
- they are capable of mixing soils containing blocks, with dimensions up to 250 mm for disc plows, 350 mm (or even 400) for blades ploughs.

### Reference CIMBETON

*photo DTP Terrassement*

*Picture 15: Blades Ploughs*

- Bladed machines (bulldozers, graders)

This type of machine is sometimes used for rough mixing.

***Animated tool mixers (Pulvimixers)***

These types of machines are sometimes called "soil pulverizer" and sometimes "in-place mixers". The most appropriate term seems to us to be "pulvimixer", which corresponds to the term used by in English speaking countries.

These materials are suitable for soil treatments:

- for backfilling specific areas: base, shoulders, technical blocks
- for pavement structure layers: TSE, capping layer, sub-base layer

The first generation horizontal shaft mixers have their mixing chamber at the rear of the machine. Those of the following generations have their mixing chamber located between the front and rear axles.

Improvements on the latest generations have focused on:

- the mixing depth (today about fifty centimetres);
- the power of the machines (up to six hundred horsepower);
- the improvement of the tools.

Some mixers are equipped with a water injection system inside the mixing chamber and a GPS guidance system.

### (1) Evolution of pulvimixers types

**GTS reference**

First generation soil pulveriser with mixing chamber at rear of tractor, maximum mixed layer thickness 0.3m (after compaction).

Second generation soil pulveriser with mixing chamber between front and rear axies, maximum mixed layer thickness 0.35m (after compaction).

Heavy 600bp (metric) third generation soil pulveriser maximum mixed layer thickness 0.5m (after compaction).

**(2) Different types of pulvimixers**


*WIRTGEN (photo DTP Terrassement)*


*PANIEN (photo Techniques de l'Ingénieur)*


*CATERPILLAR (photo Techniques de l'Ingénieur)*

*Picture 16: Pulvimixers of different types*

**Reference Cimbéton France**

**Evolution of mixing equipment**

The first machines appeared in the late 1950s and their performance was limited. Over time, they have improved enormously, in particular by increasing power and by now widespread use of servo and control devices.

Schematically, a pulvimixer consists of a tractor unit mounted on wheels and a mixer consisting of a rotor with a horizontal axis perpendicular to the direction of advance of the machine, rotating inside a containment chamber.

The oldest machines had the mixing chamber mounted behind the wheels. Models released from the late 1980s onwards have the mixing chamber located between the two axles, towards the centre of the machine.

This arrangement ensures a better penetration of the rotor in the soil and a better regularity of operation (thickness, speed, dosage).

Parallel to this evolution in design, the power of the machines has increased considerably over time. The modest machines of the early days had only 200 horsepower (135 kW); today's larger pulverizer mixers develop up to 700 horsepower (500 kW).

The greater the power, the greater the depth of treatment can be.

Thus, the first models reached - sometimes with difficulty - a mixed layer thickness of up to 30 cm (thickness after compaction).

Today, high-powered machines can guarantee a treatment thickness of up to 50 cm (after compaction).

The available power is also a crucial factor in the fineness of grinding obtained. Other factors that contribute to the fineness of the ground are the speed of the rotor (which always rotates in "lift" mode), the design of the mixing chamber and the number of tools mounted on the rotor. The rotor consists of a drum to which various types of tools can be attached. Nowadays, the tools fitted to the rotor are interchangeable, with reduced disassembly/assembly times. The different types of tools that can be used are:

- L-shaped knives, well suited for mixing fine and cohesive soils;
- spades, which are suitable for many types of soil;
- peaks, for mixing hard materials (rocky, very cohesive or hardened by pre-treatment).

In addition, the mixing chamber of modern pulverizers is equipped with a water injection device to optimize the moisture content of the mixture for compaction. Some are also equipped with a hydraulic binder suspension injection system, which eliminates the need for pre-spreading the powdered binder.

Finally, it should be noted that, for several years now, existing mixing machines have been able to be equipped with electronic systems for fine-tuning operating parameters (speeds, depth, dosages, etc.) and recording them. Highly accurate means of locating the passes (laser, GPS, etc.) are available, which guarantee the exact juxtaposition of the passes (no gaps or overlaps) and are, moreover, a valuable driving aid.

Mixing plants

*Picture 17: Mixing plant / Treatment of silts with binders for capping layer (Photo GTM Terrassement)*

*Picture 18: Mixing plant / Treatment of fly ash with binders for capping layer (Photo Techniques de l'Ingénieur)*

The majority of soil treatments are carried out by mixing in place. However, since the 1990s in Europe, particularly in France, some treatments have been carried out in central mixing plants.

The use of mixing plants is relevant for treated soils used to make sub-base and capping layers. The objective is to reach the highest formation level (platform) classes (e.g. PF 4 in the French GTR classification). The mixture must be homogeneous with a precise binder dosage, which may justify the extra cost of the use of the mixing plant.

The plants used are continuous plants, commonly used for the manufacture of pavement structure materials.

The feasibility of this treatment operation depends on the nature of the soil.

Non-cohesive or poorly cohesive soils are easily suitable for the passage through the mixing plant.

This is not the case for some clayey soils. Soils with a high clay content are problematic because they are sticky.

It can be considered that soils meeting the following specifications can be treated in a conventional plant without special equipment:

**Dmax ≤ 50 mm; Ip ≤ 12 ou VBs ≤ 1,5**

These are more or less gravelly and not very clayey soils (Reference GTR France: soils B2, B4 or B5).

More plastic soils can be treated in a mixing plant:

- either after pre-treatment in place with lime;
- or provided different improvements are made to the plant

Furthermore, as soon as the fines content is noticeable (more than about 5%) and/or the clay content is noticeable, it is highly recommended to choose a weight dosing unit, as the flows are always somewhat irregular in volume.

### 4.5.2. Choice of mixing solution

***Advantages and disadvantages of soil treatment in a mixing plant***

Treatment in a mixing plant can be considered when the equipment is available for large volumes corresponding to major infrastructure operations: motorways, high-traffic roads, logistics platforms, etc.

Treatment in a mixing plant has technical advantages resulting from the constitution of soil stocks upstream of the mixing plant, which makes it possible to carry out homogenisation operations under the best conditions.

The main disadvantage is the transport distances between the borrow pits, the mixing plant, and the application areas, which generates additional costs to be considered in the choice of this technique.

***Alternative to in-place mixing***

Successive improvements and innovations mean that today the best pulvimixers, which are also more powerful, are able to provide a high quality of mixing.

The difference with the mixing quality in the plant is much smaller than in the past. The performance of this in-place treatment equipment is now proving appropriate for many types of soil.

**Reference Cimbéton France**

**Mixing in plant / Constraints and advantages**

- ***Mixing plants layouts***

Useful arrangements to prevent clogging and ensure a regular flow of clay soil are as follows:

- use of hoppers with very steep walls;
- lining of the hopper walls with a "sliding" material (especially Teflon);
- installation of anti-arching devices (e.g. pointed hat);
- installation of vibrators where jamming is likely to occur;
- removal of possible bottlenecks.

In any case, the plant must be selected and adjusted so as to achieve a high binder dosage, significantly higher than that of hydraulic materials for conventional pavement structures. This requirement, combined with the possible problems of sticky soil flow, leads a priori to expect an effective flow rate that is significantly lower (30 to 50%) than that which the same plant producing treated gravel would have.

- ***Technical advantages***

It should be pointed out that the option of soil treatment at the plant has definite technical advantages:

- It also allows, if necessary, to eliminate the too big elements (stones or blocks) by screening before introduction in the hopper;
- Likewise, if the soil is in the form of clods, it is possible, prior to mixing, to crumble them simply by crushing them under a machine, or even by crushing them with a pulveriser or by passing them through a lump breaker;
- In addition, the moisture content of the soil can be better adjusted than with in-situ mixing, both before and in the plant;
- the mixture is more homogeneous and the binder and water dosages are better controlled, therefore more precise, than during in-situ mixing.

## 4.6. Water spreaders

- « carp tail » sprinkler: non servo-controlled
- Ramp: servo-controlled or not
- burying sprinkler
- water injection into the mixing chamber of the mixer

Carp tail sprinkler (photo NGE)

Carp tail sprinkler / large capacity tank on a scraper (photo GTR & GTS)

Feed ramp (Photo GTR & GTS)

*Picture 19: Various types of water spreaders*


(1/3)


(2/3)

(3/3)

*Picture 20: Burying sprinkler and details (photos ESTP course)*

The range of equipment generally used is briefly described below:

- water tank equipped with a carp tail
- water tank equipped with a watering ramp with or without flow meter, with or without a servo-control system
- Underground sprinkler generally equipped with a flow meter, with or without a servo system.

## 4.7. Compactors

The compaction methods depend on many parameters. It is recommended to refer to modalities generally specified and developed in a guide applicable in the concerned country (such as the GTR in France). These processes should be consulted and adapted to each configuration construction site.

The types of compactors used are:

- Vibrating compactor
- Pneumatic-tyred roller
- Sheepfoot compactor (Tamping)

We indicate in the section concerning "construction techniques" the equipment generally appropriate, depending on the nature of the treated soils, for the embankments and structural layers.

**Reference GTR**

A transverse tandem vibrating compactor of the V5 class: an original morphology allowing excellent maneuverability and optimal mobilization of masses for compaction.

A combination compactor which can be considered as the sum of a single-cylinder vibrating compactor of the V3 class and a pneumatic-tyred roller of the P1 class.

A vibrating sheepfoot compactor of the VP1 class.

*Picture 21: Vibrating compactors (Photos GTR)*

*Picture 22: Pneumatic-Tyred Roller (Photo GTM Terrassements)*

*Picture 23: Tamping (Photos DTP Terrassements)*

### 4.8. ENVIRONMENTAL PROTECTION AND SAFETY

Lime dust and hydraulic binder dust emitted during the processing work cause nuisances, which must be limited by making site arrangements.

Works contracts generally include specific clauses concerning these implementing provisions.

Better protection of the environment is also taken into account by the evolution of the equipment, as well as by the possibility of using, in the most critical cases, special treatment products such as the low-dust emission limes we mentioned earlier.

The safety of the staff must be ensured with regard to the particular risks posed by dust emissions. Preventive measures include protective clothing.

## 5. TREATMENT STUDIES / GENERALITIES AND APPLICATIONS TO DIFFERENT TYPES OF STRUCTURES

### 5.1. GENERAL CONSIDERATIONS

#### 5.1.1. Fields of application

We consider the application to the following parts of the work:

- Current embankments < 10m
- Special embankments (parts of specific structures) and high embankments
- Roadbeds and pavement structuring layers

**Reference GTS France**

The document specifically addresses road embankments, capping layers and some capping-sub-base layers included in the structural design calculation. It is consistent with the technical guide "Creation of embankments and capping layers (GTR)", the technical guide "Design and dimensioning of pavement structures" and the "Catalogue of standard structures for new pavements", published respectively in 1992, 1994 and 1998.

Its application can also be extended to similar structures such as railway or airport embankments, various earthworks for storage areas, car parks, light road foundations, industrial platforms to support rolling loads or buildings, etc. On the other hand, its use in the design and construction of earthworks with a hydraulic function (elements of dykes, dams, canals, etc.) requires special reflections and considerations that are not mentioned in the document.

**The treatment studies concerning the capping layers are detailed in the following chapter 6.**

### 5.1.2. General methodology of soil treatment studies

***Choice of treatment solution***

The decision to use the treatment to realize an embankment or a pavement structure layer such as the capping layer must be made on the basis of objective elements from:

- geotechnical studies that have two main components, material identification and mix design;
- economic studies, including the comparison of the site material treatment option with other solutions, borrowed materials or external supplies.

The decision must increasingly take account of environmental constraints, which have become more important in recent years. The balance of the treatment solution must be evaluated globally from an economic, environmental and even societal point of view.

***Progressivity of treatment studies***

Treatment studies are organized according to a pre-established program.

Within the general framework of a project, different levels are to be considered in the establishment of a treatment study program:

- At the preliminary study stage: this involves gathering and analysing the technical, economic and environmental elements that will enable us to give an answer on the feasibility of the project.
- At the preliminary design stage: the aim is to confirm the feasibility of the treatment and to provide the elements leading to the technical and economic pre-dimensioning of the project, based in particular on the geotechnical surveys.
- At the execution project stage: establish the base solution for the proposed treatment, based on detailed geotechnical studies

The specific treatment study may be initiated at any of the above stages of the study depending on the stakes of the expected responses.

| Level of study | Usual objectives of study | General points on content of study | Design phase usually concerned |
|---|---|---|---|
| 0 | Provide engineering, cost, environmental, etc. data to decide project feasibility | Collect records (geological mapping, geotechnical reports from similar jobs, etc.). Analyse it in the light of general considerations about treatment and engineering, cost, environmental, etc. particularities of project. Seek expert advice if necessary. | Project planning |
| 1 | Confirm feasibility of technique. Provide data for preliminary engineering and cost design of project | Interpret data from general geotechnical survey with reference to the soil treatment application considered and if necessary conduct a few additional reconnaissance works and classification tests. Perform quick formulation studies to determine type of additive(s) and rough additive application rate. For capping layers in particular, perform suitability tests on soil. Cost study of stabilisation solution and alternatives. | Preliminary design |
| 2 | Refine preliminary design data from level 2 study to arrive at basic tender design | Detailed geotechnical survey to qualify soils to be treated and their location in geotechnical profile. For embankment construction, perform a few additional formulation studies (depends on complexity and size of project). For capping layers, perform a level 1 formulation study (as described in § C-I-2.3.2.). | Final design |
| 3 | Provide determining engineering, cost, environmental, etc. data to validate design options not considered certain on completion of levels 0, 1 and 2 studies | Specific treatment study to:<br>- confirm on trial area the practical feasibility of soil mixing, compaction and control of dust emissions<br>- over the annual cycle, monitor soil moisture in a cut or borrow<br>- check in situ performance levels achieved by a given working method<br>- etc. | This level may be performed at one or other of the above design phases on the basis of importance of expected findings |

*Table 1: Levels to be considered in preparing programme for soil treatment design process (GTS reference)*

***Geotechnical studies***

They have two parts:

- **The qualification study of the materials to be treated** including in particular:
    - the identification of materials based on the parameters recognized as significant in relation to the treatment
    - suitability for the treatment envisaged (granularity, moisture state, proportion of deleterious elements, etc.)

It should be noted that the complexity of materials qualification studies increases rapidly with the variability of the geological context characterizing the terrains concerned.

- **The formulation study**

Its purpose is to establish the nature of the most suitable treatment product and the dosage to be introduced into the soil to obtain the desired performance for the intended application.

The dosage of the treatment product is expressed as a percentage of the mass of treatment product in relation to the sum of the masses of dry products in the mixture, according to the relation:

$$d\,\% = \frac{Q}{M_{Ss} + Q + m_{Cg}} \times 100$$

Q is the mass of the treatment product,

$M_{Ss}$ is the mass of dry or possibly pre-treated (e.g. with lime) soil,

$m_{Cg}$ is the mass of the grading corrector, if any.

A formulation study generally includes:

- Identification of the treatment product(s) used
- **Verification of the suitability of the soil to be treated with the product envisaged** is not systematic if the application of the treatment is for the reuse as backfill of soils that are too wet.
- **Determination of the dosage of the treatment product to be incorporated into the soil** according to the desired performance and, possibly, the types of binder selected and the foreseeable variations in the moisture state of the soil and its level of compaction.
- Trial areas and experimental sites.

These studies, which are part of the execution project, are to be undertaken mainly in the case of large projects, when the state of knowledge and the results of the studies at the previous stages still leave technical, economic or environmental uncertainties that are decisive in deciding on the choice of the "treatment" solution or in evaluating its cost with the required precision.

These uncertainties may include, among others, the following:

- Feasibility of mixing
- Confirmation of the announced mechanical performances, mainly for the capping layers taken into account in the design of the pavements.

Technical problems include:

- Verification of the effectiveness of a soil preparation technique (homogenization, humidification, de-stoning, etc.),
- The flowability of the material into the dosing and mixing devices of the plants.

Among the particular constraints of the worksite, let us mention the high sensitivity of the environment to dust emissions from the treatment product.

The execution of an experimental site often constitutes a major investment, which should therefore only be undertaken after a reflection on the stakes involved.

***Economic Studies***

- **Case of embankments**

For the construction of embankments, the analysis is based on the comparison of the costs corresponding to the solution of treating the wet materials and the possibility of substitution with borrowed material that can be filled without treatment.

The possibility of substitution is often difficult to envisage.

This economic analysis must also take into account the climate parameter normally foreseeable during the work and the time savings in the various solutions.

- **Soil treatment applied to the production of capping layers**

In this application, the advantage is not only to be able to use materials in capping layers which, in their natural state, do not have the required characteristics, but also to significantly increase the characteristics of materials suitable for use in capping layers without treatment, in order to reduce thicknesses and therefore quantities.

For the construction of a capping layer, treatment is therefore a possibility that should be considered almost systematically.

The economic value of the technique is to be demonstrated by a comparative cost analysis between treated and untreated capping layer solutions. It can be carried out, in broad outline, following a similar approach to that mentioned for embankments.

The economic interest is also to be considered in the participation of the capping layer in the **design of the pavement**.

***Environmental aspects***

The preservation of the environment is also to be taken into account in the choice of the treatment solution, particularly in terms of greenhouse gas emissions.

In some countries, particularly in Europe, a carbon equivalent assessment may be requested by the project owner to compare the different technical solutions envisaged.

Refer to **booklet "2E / Environmental Aspects"** of this Manual

In all cases, it is worth noting the significant positive impact of the treatment solution in terms of reducing transport and preserving natural resources.

As stressed above, this aspect must be taken into account when assessing the overall outcome of this solution.

## 5.2. Methods of treatment applicable to different parts of earthen structures

We refer to § 3 which describes the action of the different treatment products and their possible use according to the nature of the materials, in order to meet the following objectives:

- Lowering the water content,
- Insensitization to water,
- Increase of mechanical characteristics.

These objectives can be sought for the various parts of the works that we have also mentioned in §3.

It should be noted that the objective of increasing the mechanical characteristics through treatment may lead to:

- Soil improvement

  or

- Soil stabilization

(As defined in paragraph 1.5)

We consider below three types of material treatment studies for the following uses:

- Embankment core (current)
  - Only objective: lowering the water content
- Parts of specific works

  3 possible objectives:
  - Insensitivity to water
  - Improvement of physical properties (improvement)
  - Increase of mechanical characteristics (stabilization)
- Capping layers
  - Main objective: increase of mechanical characteristics (stabilization)
  - Insensitivity to water

## 5.3. SOIL TREATMENT STUDIES FOR REUSE AS BACKFILL

### 5.3.1. General methodology

The methodology to be applied to treatment studies of soil used as fill is presented below. It concerns more particularly particular embankments (parts of specific structures) consisting of treated soils with higher mechanical characteristics. However, application to soils used as common backfill is still relevant.

#### Reference France GTS

Based on the technical elements mentioned above, the content of the treatment studies carried out at the different levels of the project will generally focus on the following elements:

- At the preliminary study stage:
    - Assessment of the necessity of the treatment and its relative importance for the proposed transaction
    - Identification of possible difficulties
- At the preliminary draft stage:
    - In the perspective of the treatment, interpretation of the elements acquired within the framework of the general geological and geotechnical survey of the alignement
    - Conduct a summary formulation study on the most representative soil family(ies)
- At the execution project stage:
    - Complementary geotechnical surveys to identify all the soil formations concerned by the treatment.
    - For each formation, constitution of representative samples
    - Execution of measurements to assess the range of probable moisture states of each formation at the time of construction of the site
    - Identification, if necessary, of the treatment product used in the study
    - Carrying out a mix design study on representative samples of each formation, in order to specify the dosages to be applied according to the water content.
    - However, a more or less important part of these mix design study can be carried over to the execution studies carried out during the work.
- A project-specific level of study may be required:
    - on the one hand, when the treatment issues are decisive;
    - and, on the other hand, when the studies described in the previous stages are not able to answer correctly the questions relating to the feasibility of the treatment or its optimisation

These specific studies may include:

- Evaluation of the range of seasonal variations in the moisture state of certain soils using appropriate methods (neutron probes, capacitive probes, periodic sampling, etc.).
- Organization and conduct of an experimental treatment site, for example, in the case of:
    - the use of innovative treatment products for which no experience is available,
    - experimentation with unconfirmed execution techniques or new equipment,
    - treatment of particular soils (very clayey A4 soils, evolutive rocky materials, etc.),
    - etc.

This specific level of study can be initiated at any of the above stages depending on the stakes of the expected answers.

**Reference France GTS**

| Level of study | Content of study | Expected findings | Design phase usually concerned |
|---|---|---|---|
| 0 | Collect data from records (geological mapping, geotechnical and weather data forms, design records for similar jobsites, etc.) Collect local experience. Analyse and synthesis of these data with reference to the soil improvement technique applied to the project in hand. | Assessment of the need for treatment and its relative importance for the operation considered. Identification of possible abnormal difficulties potentially undermining the feasibility of soil treatment at the site considered. | Project planning |
| 1 | With reference to the treatment, interpret the data acquired from the geological survey and general geotechnical study of the project. If necessary, conduct some additional investigations (auger, shovel, etc.) to refine identification of the main formations involved Run quick formulation study on the (possibly two or three) most representative soil(s) families Prepare synthesis of all these data. Conduct additional geotechnical investigations to identify all the soil formations concerned by the treatment. For each identified formation, take representative samples (average soil and extreme soils). | Assessment of probable volume of soil to be treated and constructional techniques and plant that can be used. Determination of most appropriate additive(s) and quantities probably needed to an acceptable degree of precision for preliminary design in terms of engineering, cost and completion time. | Preliminary design |
| 2 | Make measurements to evaluate the range of probable moisture contents of each formation at the time construction work proceeds. If necessary, identify the additive used in the study. Conduct formulation study on samples representative of each formation to refine additive percentages to be applied with reference to moisture contents (some part of these formulation studies may be deferred to the execution studies performed during the time of construction). | Qualification of all the soils to be treated. Drafting of rules governing amounts of additive to be applied with reference to soil nature and condition. Location on geotechnical profile of each formation requiring the same construction details (techniques, plant, additives) which can be considered operationally identifiable at the time of construction. | Design |
| 3 | Evaluate range of seasonal variation of moisture content in some soils using appropriate methods (neutron probe, capacitance probe, periodic sampling, etc.) Organise and perform treatment trials, for example, in the case of: - use of novel additive(s) for which there is no experience (identification of product(s), full-scale verification of effectiveness for the job in hand, etc.) - experimenting with untried construction techniques and unfamiliar plant - treatment of special soils (very clayey soils A4, evolutive rock materials, etc.) | This level of study is specific to projects (i) in which soil stabilisation is a preponderant factor and (ii) for which lower level studies are not capable of properly clearing up doubts as to the feasibility or optimisation of the treatment. | This level may be conducted at any one of the above design phases depending on importance of the expected findings*. |

* *In particular, this level of study may be undertaken as early as the project planning phase if justified by the importance of soil improvement in preparation of the project.*

*Table 2: Levels of soil improvement studies for soil use as fill (Reference GTS)*

### 5.3.2. Treatment studies of excessively wet materials placed in backfill core

***Objective of treatment***

The main purpose of soil treatment applied to embankments is to enable the reuse of water-sensitive soils that are **too wet** to be used in acceptable technical and economic conditions at the time of extraction.

The decision to start treatment should be taken after considering the impact on the economy of the work and after considering that other methods such as aeration of the materials would not be suitable.

The optimal dosage is the one that ensures sufficient trafficability to complete the job.

In order to allow backfilling at heights ≤ 5m to 10m, one can aim for + 2% on the wet side (state h according to soil classification) which will require lower compaction energy. This provision is to be considered according to the weather conditions (more or less evaporation).

The additional stability of the structure provided by a possible hydraulic or pozzolanic setting is generally not sought in this application.

***Suitable treatment product***

- **Air lime**

The most suitable treatment product is usually calcium airlime in the form of quicklime.

In fact, it is with this product that, at a given dosage, the most important and immediate improvement in the behaviour of the soil is obtained, mainly through the concomitant action of the flocculation of the clay fraction and the reduction of the water content by hydration of the quicklime.

It should be noted that quicklime is also well adapted to the reuse of chalk that is too wet due both to the reduction in water content and to the syntaxy phenomenon which, on these materials, perpetuates the improvement in shear strength produced by the reduction in water content.

- **Other techniques**

Relatively fast-setting hydraulic binders with a high content of clinker can also be used for water-sensitive materials with little or no clay content, such as chalk, but also for gravelly and sandy soils.

Another way to reduce the moisture content of soils that are too wet is to mix them with dry or very dry fine materials such as fine sands or fly ash. This technique requires very special site conditions.

These other techniques are not developed in this chapter. We refer mainly to lime treatment.

***Desired Performance / Bearing Capacity***

<u>Natural water content ($W_n$) versus optimum moisture content ($W_{OPN}$ or OMC)</u>

Exceeding the natural water content $W_n$ in relation to $W_{OPN}$ - by 2, 4 or 6 points for example - makes it possible to define the moisture state of the materials in order to determine the appropriate dosage of lime for studies and the realization of small building sites in particular.

<u>IPI index</u>

To quantitatively characterize, at the project study stage, the conditions defining a fine moist soil - for wet to very wet materials - we recommend the use of the **Immediate bearing Index (IPI)** of the soil in situ measured at its natural water content on a specimen compacted at the Normal Proctor energy.

The method consists of measuring the IPI on the material in situ before treatment, doing a treatment study at different water contents and different lime dosages by measuring the IPI after treatment.

The test shall be carried out on the 0/20 mm fraction of the material.

This test is very interesting. It is used to determine the level of immediate trafficability and will be used to adjust the lime dosage required for backfilling by approaching the optimum water content to obtain the desired compaction without rutting.

This test applied in France is recently recommended in the European standard "Earthworks".

The objectives and performances to be sought will be different according to the classes of the too wet materials. Thresholds of IPI values before and after treatment can be defined for the different classes (values increasing from fine materials to more clayey and more structured materials).

An example of a value table is provided here after:

### Reference France GTS

| | Materials classes (in GTR 92 classification) | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| | $A_1$<br>$C_1A_1$<br>$C_2A_1$ ● | $A_2$<br>$B_6$<br>$C_1A_2$<br>$C_2A_2$ ●<br>$C_1B_6$<br>$C_2B_6$<br>$R_{34}$ | $A_3$<br>$C_1A_3$<br>$C_2A_3$ ● | $B_4$<br>$C_1B_4$<br>$C_2B_4$ ● | $B_2$<br>$B_5$<br>$C_1B_2$<br>$C_2B_2$ ●<br>$C_1B_5$<br>$C_2B_5$ ● | $R_{12}$ ○ | $R_{13}$ ○ | $F_2$ |
| Values below which treatment can be considered (cf GTR) | 8 | 5 | 3 | 15 | 12 | 15 | 10 | 15 |
| Values to be achieved on treated material ✧ | 10 to 20 | 7 to 15 | 5 to 10 | 20 to 40 | 15 to 30 | 15 to 30 | 10 to 20 | 15 to 20 |
| Values beyond which treatment can be discontinued (or pursued with less additive) | 15 to 25 | 10 to 20 | 8 to 15 | 30 to 50 | 20 to 40 | 25 to 35 | 15 to 25 | 25 to 30 |

● Materials in these classes contain a large fraction of angular grains larger than 20 mm. Therefore, estimating their bearing capacity from their IPI value measured on their 0/20 mm fraction may not be sufficiently representative. A more precise evaluation would require in situ tests (plate bearing tests or dynaplate tests, etc.)

○ The values shown for R classes are not issued from GTR, they are indicative only. For classes of water-sensitive materials not shown in the table, IPI values to be considered must come from a specific study

✧ For subgrade treatment, values must be increased by 10% to 20%, and the $I_{CBR}$/IPI ≥ 1 condition must be met (cf. §B-2.2)

*Table 3: Objectives of soil improvement applied to use of too wet soils in fill, assessed by immediate bearing index (IPI)*

Treatment increases the IPI (multiplied by 2 to 3).

### Reference GTS

The instant bearing capacity IPI of the soil at natural moisture content is frequently the best parameter at the design stage for determining the additive demand.

*Picture 24: IPI test (similar to Immediate CBR test but without surcharge)*

The immediate bearing index (IPI) of the soil at its natural water content is the parameter that, at the study stage, is often the most suitable for determining the dosage of the treatment product to be introduced into the soil.

***Geotechnical studies to be undertaken***

The preceding table specifies the general content of the different levels of geotechnical studies and in correspondence, the project development phase where they are usually engaged. In particular:

- **The soil recognition and qualification study**

It is important to note that the reliability of the treatment for the applications envisaged is all the greater as the moisture state of the concerned materials is between medium and wet.

The soil moisture state observed at the time of implementation must be reduced to the medium state or even wet state - up to + 2 points on the wet side - and not on the dry side, which would call into question the validity of the treatment envisaged.

- **Consideration of meteorology**

A meteorological study of the site - based on statistical data or records from nearby construction sites - is justified when it comes to soil treatment. Such a study includes the establishment of the annual "precipitation-evaporation" water balance and makes it possible to specify the periods of the year that are most suitable for carrying out treatment work.

- **The mix design study**

It is a question of establishing a decision grid with an identified treatment product (standard or product data sheet) showing the evolution of the immediate bearing index (IPI) according to the lime dosage for different water contents of the soil.

An example of the presentation of the results of a mix design study is provided below.

## Reference France GTS

### Determination of an optimum lime dosage

In this case, it is a case of lime treatment of a **fine silt type A2 soil** according to the GTR classification (see synoptic § 6) with the following characteristics:

**Dmax ≤ 50 mm et (% < 80 µm) > 35 %**

**12 < IP ≤ 25 ou 2,5 < VBS ≤ 6**

The methodology of the formulation study presented consists in moistening the 0/20 mm fraction of the samples, constituted during the qualification study, to three water contents (as far as possible, the extreme values of the range of foreseeable water states for the period of execution and the average of the values measured during the surveys are retained).

The samples prepared in this way are mixed with increasing amounts of treatment products (at least three dosages per water content) chosen within a realistic economic range. For the general case where the treatment product is quicklime, it is accepted that studies should not be conducted above dosages of 4-5%.

Each mixture is then compacted according to the operating conditions defined in a standard and the IPI value of each is determined.

**Table 4 Example of presentation of results of a soil treatment mix design study (Class A2 silt) for reuse as backfill**

**Table of parameters measured during a soil treatment mix design study for "backfill reuse".**

| **Parameters** (1) | | **Lime dosages (%)** | | | | |
|---|---|---|---|---|---|---|
| | | 0 | 0,5 | 1 | 2 | 4 |
| $W_n$ of the soil: 18% | **IPI** | **3** | **15** | **23,5** | **35,5** | **27** |
| | $W_{treated\ soil}$ (%) | 18,1 | 17,6 | 17,1 | 16,4 | 14,7 |
| | $\rho_d$ (t/m3) | 1,73 | 1,73 | 1,70 | 1,67 | 1,57 |
| $W_n$ of the soil: 20% | **IPI** | **2** | **5,5** | **14** | **23,5** | **23,5** |
| | $W_{treated\ soil}$ (%) | 19,7 | 19,6 | 19,3 | 18,7 | 17,4 |
| | $\rho_d$ (t/m3) | 1,67 | 1,69 | 1,69 | 1,68 | 1,61 |
| $W_n$ of the soil: 24% | **IPI** | **0,5** | **1,5** | **2,5** | **5** | **13** |
| | $W_{treated\ soil}$ (%) | 24,1 | 23,7 | 23,1 | 21,7 | 20,5 |
| | $\rho_d$ (t/m3) | 1,56 | 1,57 | 1,59 | 1,63 | 1,63 |

(1) $\rho_d$: dry density

*Table 4: Example of presentation of results of a mix design study*

### Presentations of the two abacuses of the lime treatment study

Evolution of the immediate bearing index (IPI) as a function of the lime dosage for different soil water contents.

Lime dosages necessary to obtain an immediate bearing index (IPI) of 5, 10 or 15 depending on the water content of the soil (without taking into account the evaporation produced during mixing).

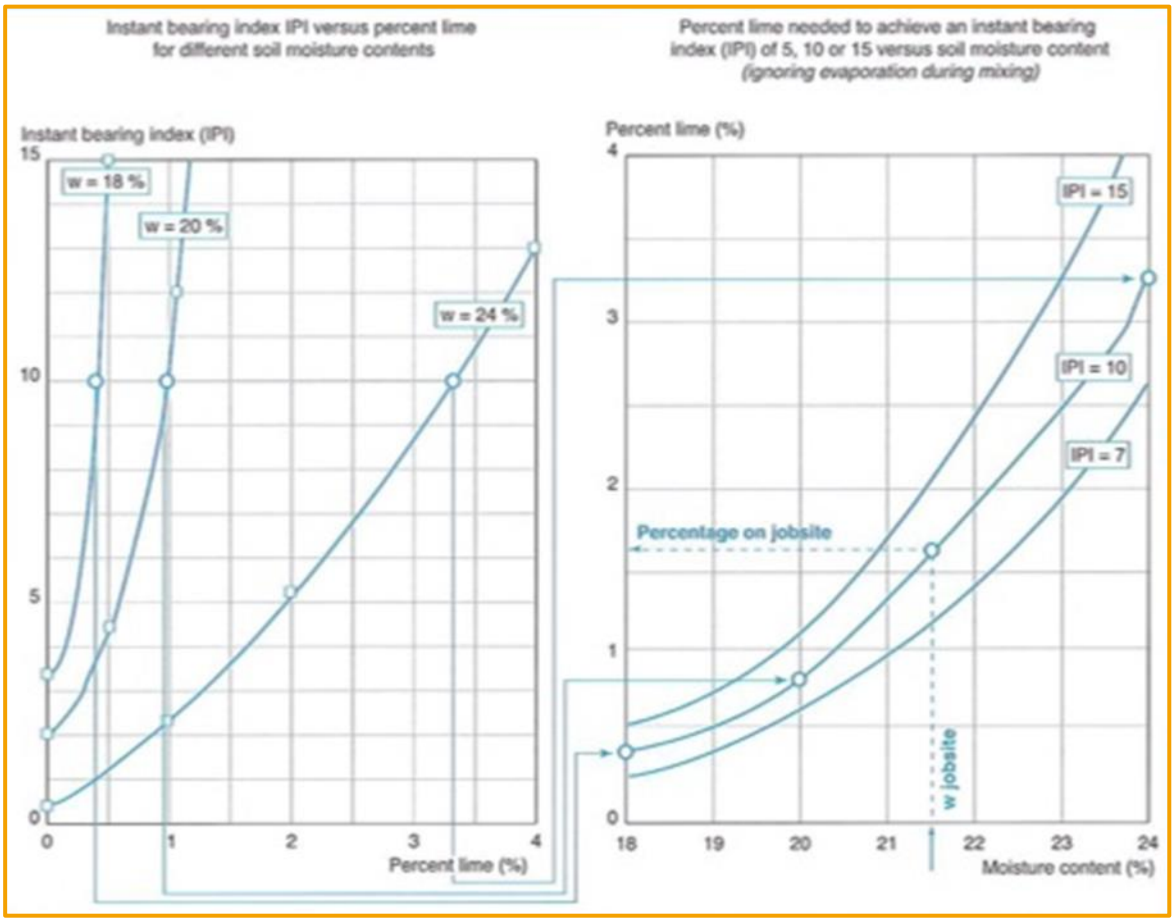



*Figure 6: Immediate Bearing Index*

- **Presence of disturbing elements**

If the geological context shows a significative probability of presence of disturbing elements (organic matter, sulphates, etc.) in the material, a vérification of the **suitability of the material to be treated** will be engaged in order to detect possible swellings (Cf test carried out in France according to standard NF P94-100 / Standard EN in preparation).

The methodology of this test is mentioned in the European standard "Earthworks".

The limit for swelling must be below a threshold set by the rules in the country concerned.

Booklet “2A / Materials” of the Earthworks Manual presents the practices of some countries in this field.

**Example France:** this threshold is set at 5%. Beyond this value, it confers a doubtful character to the treatment suitability of the studied material. However, in the case of swelling between 5 and 10%, treatment may still be considered, subject to conclusive results from further studies.

**European Standard References** (See Appendices 3 and 4)

***Economic study***

On the basis of the results of the geotechnical and meteorological studies, the economic evaluation of the treatment solution should be carried out and compared with the possible alternative solutions on the site under consideration.

***Environmental performance***

As highlighted above, an environmental performance must be carried out to make an overall assessment, together with the economic p of the treatment option in relation to other alternatives.

## 5.4. WATER DESENSITIZING TREATMENTS FOR USE IN CERTAIN PARTS OF STRUCTURES

### 5.4.1. Soil classes suitable for this type of treatment

Soils that can benefit from the action of air lime to make them insensitive to water are clay soils of medium to high plasticity (Cf paragraph 2.1).

#### Example Reference France

Referring to the GTR material classification, the classes of materials suitable for treatment for water desensitisation, taking into account their argillaceous nature, are generally as follows:

Classes (Ci ) A1-A2-A3 or even some A4

B2 B5-B6 provided that the **VBS** value **> 0,5**

### 5.4.2. Objective for bearing capacity

The criterion for a material rendered insensitive to water is as follows:

$$\mathbf{I_{CBR} / IPI \geq 1}$$

CBR Index

In most countries, the CBR Index or CBRi (after 4 days of immersion) is used to characterize the soil to be treated.

Lime treatment increases the value of the IPI very significantly (3 to 4 times).

Plate tests can be carried out as a verification.

This type of treatment can be applied to structuring layers:

- Top Section of Earthworks (TSE)
- Capping layer possibly under certain conditions

It also applies to parts of specific works

- Embankment bases in wet areas or areas subject to flooding, without stability conditions (Height < 10 m)
- Technical blocks for civil engineering or hydraulic works in some cases (no problem of slope for 2 for 1)

### 5.4.3. Top Section of Earthworks (TSE)

**Water insensitization applied to TSE Materials**

Improvement of the bearing capacity of the TSE

Where the TSE consists of water-sensitive materials of poor bearing capacity prior to the application of the capping layer, provision is made for the possibility of improving it to a thickness of at least 30 cm by a soil treatment carried out using an "embankment" technique.

TSE in the cut

When TSE materials are too wet, to avoid expensive material substitution, appropriate techniques may be aeration, drainage or, if this is not sufficient, lime treatment.

For moderately to highly plastic materials, the lime treatment carried out on one or two layers (35 cm thick for each layer) makes it possible to reduce the moisture state of a material from h or th to the m state.

This method can be used to obtain a layer with a certain bearing capacity, which will determine the design of the form layer.

TSE on the fill

The method is identical when proceeding on materials that have generally been previously treated in the cut or on the backfill.

## Reference France

| Application | Significant assessment criterion | Target threshold values | Remarks |
|---|---|---|---|
| Improved subgrade | IPI<br>+<br>$I_{CBR}$<br>after 4 days soaking | Depend on soil nature<br>In absence of particular experience, target values might be the IPI values to be achieved on treated material shown in Table B-I plus 20% approx.<br>Values of $I_{CBR}$ after four days soaking must be at least equal to IPI values at moisture content considered | Conservation of (or, better, increased in) IPI values after 4 days soaking is an assurance that the effects of treatment will be durable |

*Table 5: Performance to look for in treatment applications*
*Case of TSE*

Bearing capacity objective for a water-insensitized TSE

The water-insensitized TSE (in a perennial way) allows to obtain a level of subformation level which constitutes the subgrade of the capping layer and must respect minimum thresholds before the implementation of the capping layer.

These thresholds correspond to the values determined by static deformation tests on the EV2 plate. Another type of test allows to evaluate the bearing capacity of the subformation level: the dynamic modulus measured with the dynaplate.

A first level of these thresholds (AR 1) is as follows:

- for a granular capping layer: EV2 ≥ 15 à 20 MPa;
- for a treated capping layer: **EV2 > 35 MPa**, for the case that interests us here. This class does not contribute to the dimensioning of the pavement structure.

In some cases, desensitized TSE may be sufficient to achieve the second level of arase (AR 2), i.e.:

- for a treated capping layer: **EV2 > 50 MPa**

This class of subformation level allows to participate in the dimensioning of the pavement structure, provided the soils are not very frosty, or not frosty at all.

### Reference France GTR

**EV2**

| Calculation Module (MPa) | 20 | 50 | 120 | 200 |
|---|---|---|---|---|
| Subformation layer classe | AR1 | AR2 | AR3 | AR4 |

Please note:

- AR3 exceptional
- AR3 and AR4 granular/rock materials

## 5.4.4. Capping layer

**Insensitization to water applied to the capping layer materials**

The bearing capacity objective of the capping layer is generally sought in order to participate economically in the design of the pavement structure. This usually involves a stabilisation operation (increasing the long-term mechanical characteristics) of the available soils suitable for constituting this structuring layer by an appropriate treatment with hydraulic or mixed binders, lime and hydraulic binders. (Cf. § 6 of the present booklet).

In some cases, water desensitization with lime may be sufficient to achieve the desired bearing capacity for the use of soils in capping layers, provided there are no frost resistance constraints (very shallow frost depth zones).

### 5.4.5. Parts of specific works

**Water desensitization applied to materials constituting certain parts of structures**

Embankment bases in floodable areas and humid areas, as well as the technical blocks treated for this purpose, must not have stability conditions that would require an increase in mechanical characteristics. (See next paragraph).

## 5.5. OTHER APPLICATIONS OF SOIL TREATMENT IN THE CONSTRUCTION OF SPECIFIC PARTS OF STRUCTURES BY INCREASING THE MECHANICAL CHARACTERISTICS (STABILIZATION)

### 5.5.1. Objectives of treatment

Soil treatment may also be considered for particular parts of a fill, even if the concerned soil is in a moisture state allowing it to be used. The objective is then to obtain, through treatment, a more or less high but definitive stiffening of the treated material, in order to give it the mechanical characteristics that can be taken into account in the design of the structure.

### 5.5.2. Parts of works concerned

The improvement of the mechanical characteristics of the materials is practised with a view to their use in the construction of certain specific **parts of works**:

- embankments in difficult-to-reach areas (embankments adjacent to engineering structures, sewerage works, etc.);
- low parts of high embankments with water-sensitive soils;
- embankments made of evolutive rock materials, possibly if necessary in addition to mechanical treatment (particle size reduction);
- slope stiffening;
- retaining blocks, weight masks with draining screen, …

The treatment can also be carried out on the **tops section of earthworks** (TSE) to improve its mechanical characteristics:

- possibly in some cases to correct an excessively high moisture state of the materials
- but also, if necessary, to improve its mechanical characteristics and to obtain a bearing capacity of the subgrade, which can be used for the design of the pavement against frost

  (See France reference class of subformation level in paragraph 5.4.3)

  Mainly:

  - embankments adjacent to engineering structures (technical blocks)
  - Culvert wedging backfill (technical blocks)
  - trench backfills

More generally, this concerns all embankments made in narrow areas that do not allow normal evolution of the equipment and paricularly the compaction equipment. In this case, the treatment is intended to give the materials a permanent cohesion that can compensate for possible localized compaction deficiencies, which are always difficult to avoid in these areas.

*Lime treatment of the TSE of a railway track (reconstruction of a second track)*
*Picture 25: Embankment in confined area*

**Stiffening of embankment slopes**

Since the treatment gives a soil a permanent cohesion that can be adjusted to the desired level, it is possible with treated soils to stiffen the embankment slopes (to reduce the right-of-way of these structures, for example).

*Sides of cut in silt supported with hyfraulic binder stabilized chalk (Photo GTS)*
*Picture 26: Slope stiffening*

**Realisation of the lower parts of high embankments**

This is particularly the case for embankments built with water-sensitive soils or with certain evolutive rock materials.

The rock materials concerned include those of the classes:

$R_{12}$, $R_{13}$, $R_{23}$, $R_{34}$, $R_{64}$

and particularly when the hydrological conditions at the site suggest the possibility that the lower portion of the embankment may be temporarily flooded during the life of the structure.

The action sought in the treatment is a cementing of the elements of the material, in order to avoid deformations resulting from rearrangements due to fractures caused by the combined action of water and mechanical stresses.


*Picture 27: Evolutive materials / Pelites*
*(Reference AIPCR RT 2012)*

### 5.5.3. Treatment products

The binders that can be used for all the types of parts of the works we have just mentioned are hydraulic binders, cements in some countries, but mainly HRB. The components of HRB other than clinker: fly ash, lime, slag, ...give them interesting characteristics for different types of treatment.

Example: Germany mainly uses lime-based road binders.

However, lime alone can be used in some cases, for example:

- Contiguous embankments when the slope is 2:1 or even 3:2.
- High embankment bases when the compressive strength is greater than 0.5 MPa.

Generally accepted thresholds depending on the height of the embankment:

- 10 to 15 m Rc > 0,5 MPa
- 15 to 20 m Rc > 0,8 MPa
- > 20m Rc > 1 MPa

And more, depending on the final height of the embankment.

A mixed lime-hydraulic binder treatment can also be adapted for certain performance objectives.

### 5.5.4. Performances to look for

Parts of particular works must must meet requirements, usually prescribed by written contract documents.

Generally speaking, they depend on the application under consideration and the particularities of the project and, for this reason, should as far as possible be determined by a specific study.

The significant criterion is compressive strength:

**Rc at 28 days**

Table 6 below provides indicative values that can be used as a guide in the absence of a specific study.

**Reference France**

| Application | Significant assessment criterion | Target threshold values | Remarks |
|---|---|---|---|
| Filling in inaccessible places | $R_c$ at 28 days | Tests to be done on samples of aspect ratio 2, compacted to $\rho d = 95\% \rho d_{OPN}$<br>Values to be achieved after 14 days curing + 14 days soaking ≥ 0.5 to 1 MPa (depending on fill volume) | Verify that, with the additive content providing the required Rc values, the corresponding IPI also meets the values shown in Table B-I |
| Lower parts of high embankments built of water-sensitive or evolutive materials | $R_c$ at 28 days | As above<br>(but required values must be set on basis of height of embankment) | As above + verification, when using evolutive materials, that strength of the material before treatment (measured on blocks) is not less than the target value |
| Embankment slopes steepening | $R_c$ at 2 days + $R_c$ at 28 days | Values to be determined by specific soil mechanical study allowing for geometric characteristics (height and face slope) and constructional method | The 2-day $R_c$ to be specified must be such as to allow construction to proceed if no special measures (temporary shuttering, etc.) are provided. This value is not specified if the slope is to be cut to its final line after the mixture has set sufficiently |

*Table 6: Performances to be sought for soil treatment applications in backfilling*
*Increased mechanical performance*

# 6. TREATMENT STUDIES OF MATERIALS FOR CAPPING LAYER

## 6.1. INTRODUCTION

### 6.1.1. Conditions of use materials for capping layer

A soil, rock material or industrial by-product can be considered suitable for capping layer when it meets four conditions:

- insensitivity to water,
- granularity compatible with the levelling requirements of the platform,
- resistance to site traffic,
- no swelling due to frost, if any.

Generally, only a small proportion of the material from cuttings or borrow material naturally meets these conditions.

For most of the materials available on the construction site, it is necessary to improve their behaviour by an appropriate technique and, in particular, by treatment with lime and/or hydraulic binders.

This technique makes it possible to confer on materials which, for some, would not even be usable as backfill, performance largely higher to those of natural granular materials traditionally reserved for the realization of capping layers.

It should be noted that the treatment technique can also be applied to natural granular materials to enhance their performance and optimize the design of a particular project.

The technique of treatment for the realization of capping layers is therefore of interest for the majority of soils and rock materials.

### 6.1.2. References

For the content of this paragraph, we refer mainly to the French practice, which covers all the procedures for the design, study and construction of the capping layer for optimum use in the pavement structure. This practice was largely extended in Europe with the establishment of the 'Earthworks' standard published by CEN (1 ).

The reference for the treatments is the technical guide "Soil treatment with lime and/or hydraulic binders" (GTS).

The classification of the materials taken into account in this guide is that of the GTR (Technical Guide "Construction of embankments and capping layers") according to the synoptic table below, which enables a correspondence to be established with the classifications applied in other countries.

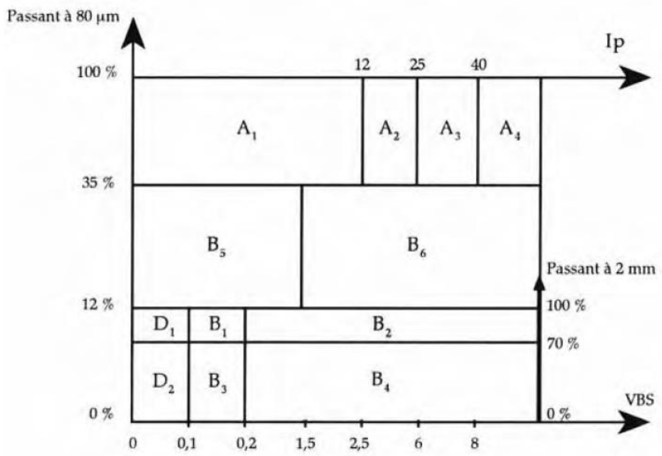
(1) **Earthworks standard in 6 parts, published in English in 2018**
**French version published by AFNOR in December 2019**

**EN 16907- 4: Earthworks - Soil treatment with lime and/or hydraulic binders**

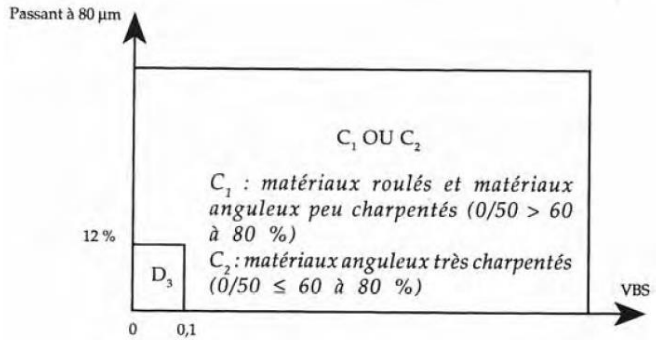
## Material classes (reference GTR France)

Tableau synoptique de la classification des matériaux
selon leur nature

Sols
Dmax ≤ 50 mm




Sols
Dmax > 50 mm




Matériaux rocheux

| | | | |
|---|---|---|---|
| Roches sédimentaires | Roches carbonatées | Craies | $R_1$ |
| | | Calcaires | $R_2$ |
| | Roches argileuses | Marnes, argilites, pélites ... | $R_3$ |
| | Roches siliceuses | Grès, poudingues, brèches ... | $R_4$ |
| | Roches salines | Sel gemme, gypse | $R_5$ |
| Roches magmatiques et métamorphiques | Granites, basaltes, andésites, gneiss, schistes métamorphiques et ardoisiers ... | | $R_6$ |

Matériaux particuliers

| | |
|---|---|
| Sols organiques et sous-produits industriels | F |

*Figure 7: GTR material classes*

## 6.2. General methodology for capping layer studies

### 6.2.1. General Context / Progressiveness of Studies

The studies applied to the realization of capping layers in treated soils require important delays, in particular because of the setting and hardening times to be respected.

The volume of these studies is all the more important as greater participation of the capping layer in the design of the pavement is sought.

### 6.2.2. Importance of building sites

***Small construction sites***

First of all, it should be pointed out that for small sites, the cost and time required for treatment studies, in particular, mix design are often incompatible with the economics of these sites. In this case, the interest of the soil treatment solution can be validated empirically, by determining the type of treatment product and its dosage according to the soil class, using modalities - when they exist in the country concerned - based on experience feedback, guides, etc.

**Reference France as an example**

| Soil class | Treatment method |
|---|---|
| $A_1$•, $B_5$•<br>$C_1A_1$•, $C_1B_5$•<br>$C_2A_1$•, $C_2B_5$• | 1% CaO + 7% $C_{32,5}$ |
| $A_2$, $B_6$<br>$C_1A_2$, $C_1B_6$<br>$C_2A_2$, $C_2B_6$ | 1,5% CaO + 7% $C_{32,5}$ |
| $A_3$, $C_1A_3$, $C_2A_3$ | 2% CaO + 7% $C_{32,5}$ or 6% CaO |
| $B_1$, $B_2$, $D_1$<br>$C_1B_1$, $C_1B_2$ | 6% $C_{32,5}$ + corrector of granular material ✪ |
| $B_3$, $B_4$, $D_2$, $D_3$<br>$C_1B_3$, $C_1B_4$<br>$C_2B_3$, $C_2B_4$ | 5% $C_{32,5}$ |
| Other materials | To be specified on the basis of a level 1 study at least |

• If these materials contain little clay ($VB_S < 0.5$), lime treatment is not essential.
✪ Choice of corrector type and percentage (if any) must refer to local experience.

❶ Designation as per French Standard NF P 15-301, 1994 (cf : appendix 2).

❷ This fraction is generally the whole soil in the case of class A3 soils, but this is not the case for class C1A3 and C2A3. For these classes, one must estimate, at least approximately, the proportion of 0/400 µm faction and correct accordingly the 6% value given in table C1-V (otherwise, the additive demand will be overestimated and if the additive is lime, it will not help improve the mechanical characteristics).

*Table 7: Possible treatment modalities for small construction sites*

***Major construction sites***

In the remainder of this chapter, we focus on larger sites where the economic relevance of treatment solutions is proven. Different stages of treatment studies need to be considered.

**The main study phases**

- **Identification and characterization of the deposit (see § 6.3)**

When the decision has been made to create a capping layer in treated soil (generally at the end of the preliminary design study), the deposit from which the materials to be treated will be extracted must be characterized.

The deposit of materials capable of forming capping layers after treatment is determined on the basis of an economic study. This may be project excavation, site borrow pits, or a previously established material deposit.

The identification and the characterization of a deposit are necessary to highlight the quality and the useful quantity of materials for the good progress of the construction site. The quality of the deposit is essentially dependent on the identification and classification of the materials, including the homogeneity of their nature and state, in order to facilitate extraction methods.

- **Assessment of the suitability of the material for treatment (see § 6.4)**

Prior to conducting treatment studies, the geotechnician must ensure the suitability of the materials under consideration for treatment.

- **Mix design (see § 6.5)**

The mix design study, allowing the selection of the most suitable treatment product and the determination of the dosage necessary to achieve the targeted performance objectives, can be initiated. It is necessary for construction sites of a certain importance.

Its extent depends on the greater or lesser involvement of the capping layer in the pavement structure and the experience already available on the behaviour of the mix under consideration.

Three levels of formulation studies can thus be envisaged:

- level 1, which allows verification of the adequacy of the performance obtained with the objectives set in the short and long term
- Level 2, which involves determining the binder dosages and optimising the performance to be achieved;
- level 3 which concerns the design of the capping layers according to the calculation of pavement structures.

We propose below to develop these different aspects based on methods applied in France and Europe.

## 6.3. CHARACTERIZATION OF A DEPOSIT

### 6.3.1. General terms and conditions

In order to consider the use of a treated soil in capping layer, it is first necessary to know, with sufficient precision, the ranges of variation of its main geotechnical characteristics within the deposit intended to be reserved for this use.

For this purpose, a geotechnical survey based on a minimum number of measurements, depending on the volume of material and the level of knowledge that may be available a priori, is essential.

| Level of survey | Content of survey | Expected answers | Stage in design process normally concerned |
|---|---|---|---|
| 0 | Collect available documentary data (geological maps, geotechnical and meteorological data files, design documents from comparable jobs, etc.)<br>Collect local knowledge (especially on possible presence of harmful soil components and, if present, perform a few tests to assess the suitability of the soil for the proposed treatment)<br>Analyse and collate this data in the light of soil stabilisation applied to the proposed capping layer project | Technical possibility of considering constructing a stabilised soil capping layer (sufficient quantities of materials and suitability of the materials for treatment)<br>Detection of possible unusual difficulties liable to invalidate the feasibility of soil stabilisation on the site considered (possibilities for mixing for example) | Project planning |
| 1 | Make brief characterisation of deposit to be used for the capping layer on the basis of data from the general geological and geotechnical survey of the project<br>If necessary, sink a few additional auger or drilling holes, etc. for a more refined characterisation of the deposit<br>On large jobs, run a quick formulation study on 1 (or perhaps 2 or 3) sample(s) representative of the deposit(s) to be used for the capping layer. Collate all this data | Confirmation of suitability for treatment of soil in the deposit to be used for the capping layer<br>Evaluation:<br>- of probable useable soil volumes<br>- of constructional plant and techniques<br>- of most appropriate additive(s) and quantities probably needed<br>with enough precision for preliminary design (technical, cost, completion time, etc.) | Preliminary design |
| 2 | Finalise the characterisation of the deposit as described in § C1-2<br>For each deposit, make up representative samples (average soil and extreme soils)<br>Identify if necessary the additive used in the study<br>If justified by the project (cf § C1-2), perform a formulation study of the appropriate level on samples representative of each deposit in order to determine the additive application rates required to achieve the desired performance and if applicable expected moisture contents (part of the formulation studies may be postponed until the construction studies performed during the construction work if the study time so permits) | Formulation of rules on additive percentages required with reference to soil nature and condition and target level of mechanical performance<br>Characterisation and location of deposits on the geotechnical longitudinal profile<br>Data on the most appropriate constructional plant and methods in technical terms | Design project |
| 3 | Organise and perform field trial, for example, to validate:<br>- the design of the capping layer plus pavement when the design method is based on performance determined in the laboratory. In this case, the field trial should include, in addition to the routine inspections and tests normally conducted for a stabilised soil capping layer job, measurements of mechanical performance on cores and/or ovalisation measurements<br>- the use of innovative additive(s) about which there is no past experience (identification of product(s), measurement on cores or by ovalisation of performance achieved, etc.)<br>- the use of special constructional plant and techniques (stabilisation plant mixing, special types of compactors, etc.)<br>- trials of unproved constructional techniques or poorly-documented plant<br>- the choice of the stabilisation alternative for certain soil of poorly-documented behaviour (for example: evolutive rock materials, high clay content soils, soil probably containing harmful components, etc.)<br>- etc. | This level is specific to projects for which lower levels of study have not yielded sufficiently precise answers to questions as for the feasibility of soil stabilisation treatment and as regards inclusion of the stabilised soil capping layer in the pavement design when these aspects are determining factors in the project | This level of study may be performed at any stage in the design process depending on the importance of the results sought* |

*In particular, when the soil stabilisation stake is sufficiently important, this level of study may be performed at the project planning stage

*Table 8: Different levels of geotechnical survey required for stabilized soil capping layer applications*

If the ranges of variation thus revealed exceed certain thresholds, consideration should be given to whether a sorting and/or homogenisation technique would be able to reduce them to meet the proposed thresholds.

In this paragraph, the aspect mainly considered is that of a natural deposit (excavated or borrowed), but the elements developed here are applicable almost entirely to all places of origin from which the materials to be studied for treatment may come (deposits, stocks, etc.).

### 6.3.2. Methodology

The general objective is to:

- **define** on a geotechnical profile, the zoning of each formation and, within a zone, the range of variation of soil nature and condition parameters
- **provide** a representative sample of each zone (or a mixture of several zones) on which mix design study (performance measurement) can be carried out

**Example Reference GTS**

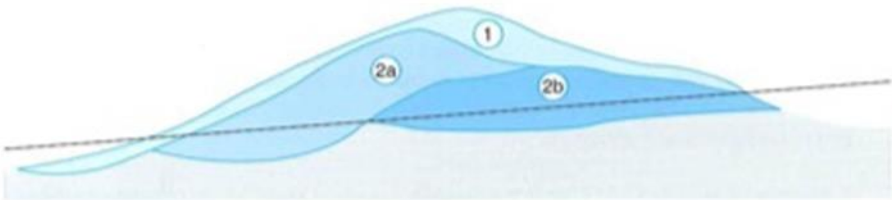



*Figure CI-1*
*Example of presentation of geotechnical longitudinal profile for stabilised soil capping layer project*

| Deposit zoning | 1 | | | 2a | | | 2b | | |
|---|---|---|---|---|---|---|---|---|---|
| Geological formation | Aeolian silt | | | Marly clays | | | Marly clays | | |
| Estimated volume | 120 000 m³ | | | 50 000 m³ | | | 40 000 m³ | | |
| | Mean | Scatter ● | Number of measurements | Mean | Scatter ● | Number of measurements | Mean | Scatter ● | Number of measurements |
| $VB_s$ (g) | 1,65 | 18% | 16 | - | - | - | - | - | - |
| $I_p$ | - | - | - | 18 | 33% | 12 | 25 | 40% | 6 |
| $W_n$ (%) | 16 | 25% | 40 | 19 | 10,5% | 18 | 26 | 34,5% | 12 |
| $W_{OPN}$ (%) | 16 | 12,5% | 12 | 18 | 17% | 8 | 24 | 21% | 6 |
| $\rho d_{OPN}$ (g/cm³) | 1,76 | 4,5% | 12 | 1,72 | 7% | 8 | 1,66 | 8,5% | 6 |
| IPI à $W_n$ | 14 | 57% | 12 | 8 | 62,5% | 8 | 5 | 80% | 6 |
| GTR class | A1 | | | A2 | | | A2-A3 | | |

● Scatter is expressed as the ratio between the measurement range, if the number of measurements N is < 10 (or twice the standard deviation if N > 10) and the mean of measurements.

*Figure 8: Example of geotechnical longitudinal profile / Characterization of a capping layer deposit*

***Geotechnical survey for characterizing a deposit***

The deposit selected for treatment must be characterized by a minimum of geotechnical identification tests which is a function of the volume of material required and the level of prior knowledge of the formation under consideration.

### Example Reference GTS

In the absence of other indications, the minimum number of tests can be assessed from the elements in the table below.

| Volume (V) of planned capping layer ($m^3$) | Geotechnical classification tests | Formation known and assumed uniform ✧ | Formation known and assumed moderately uniform ✧ | Formation unknown |
|---|---|---|---|---|
| $V < 10^4$ | Soil nature ●<br>Moisture state ○ | 1<br>2 | 3<br>4 | 9<br>16 |
| $10^4 < V < 10^5$ | Soil nature ●<br>Moisture state ○ | $V / 10^4$<br>$2V / 10^4$ | $3V / 10^4$<br>$4V / 10^4$ | $9V / 10^4$<br>$16V / 10^4$ |
| $V > 10^5$ | Soil nature ●<br>Moisture state ○ | 10<br>20 | 30<br>40 | 90<br>160 |

● The tests concerned here are those for classifying the soil according to its nature under the classification system described in French Standard NF P 11-300.

○ Chiefly estimated from measurements of natural moisture content assumed to be representative of the construction season. If the time of construction is not known and this is an influencing factor (shallow deposit, deposit affected by annual fluctuations of the water table, for example), careful thought, preferably based on tests and inspections, is needed to estimate, over the annual cycle, possible extreme moisture contents.

✧ This assessment is assumed to come from a geotechnical engineer with good knowledge of local formations

*Table 9: Minimum level of tests needed to characterize a deposit*

***Exploitation of geotechnical reconnaissance data***

- **Taking into account variation**

For each deposit, a histogram of the nature and water content test results should be compiled and the mean m and standard deviation a (or the extent of variation of the measurements if there are fewer than 10) should be determined. When the distribution has a multimodal distribution, it should be checked whether a breakdown of the histogram can correspond to a simple zoning that can be identified during the work.

### Reference / Feedback (PIARC Technical Report 2012) in booklet "2A.II - Marginal materials" of the Eartworks Manual

- **Constitution of representative samples**

Before the representative sample for the processing study is compiled, the homogeneity of the material in the deposit selected for processing should be assessed. To do this, the dispersion of the **þ$_d$OPN** values measured on the various samples taken from this deposit is determined.

## 6.4. ASSESSMENT OF SOIL SUITABILITY FOR TREATMENT

In the application of the treatment for the realization of capping layers, the suitability for treatment of the soil should be checked almost systematically and this should be done at a project development phase, all the more so as doubts on this point are possible.

This verification shall be based on a standard test.

### Reference France and Europe

Soil treatment suitability test

### Standard NF P 94-100 (European Standard NE 13290 part 49)

The results of the test shall be interpreted as shown in the table below.

| Treatment type | Suitability of soil | Parameter considered Volume swelling Gv (%) | Brazilian strength Rtb (MPa) |
|---|---|---|---|
| Treatment with hydraulic binder (maybe combined with lime) | Suitable<br>Marginal<br>Unsuitable | $\leq 5$<br>$5 \leq G_v \leq 10$<br>$\geq 10$ | $\geq 0{,}2$<br>$0{,}1 \leq R_{tb} \leq 0{,}2$<br>$\leq 0{,}1$ |
| Treatment with lime alone | Suitable<br>Marginal<br>Unsuitable | $\leq 5$<br>$5 \leq G_v \leq 10$<br>$\geq 10$ | Parameter not considered for this type of treatment because of slow pozzolanic setting time*. |

*The test applied to soil concerned in this type of treatment only yields information on potential ettringite swelling. Proper development of the pozzolanic set can however be assessed in a comparable time by the Proctor-IPI-$I_{CBR}$ study (cf § 3.6.1.)

*Table 10: Criteria for interpreting the "soil suitability for treatment" test*

The test includes a measurement of the volume swelling and an assessment of the proper functioning of the hydraulic connection.

- **In cases designated as "unsuitable"**

The treatment technique should in principle be abandoned (unless a specific binder is chosen or the soil is modified by an appropriate treatment such as pre-treatment with lime, for example).

- **In cases designated as "doubtful"**

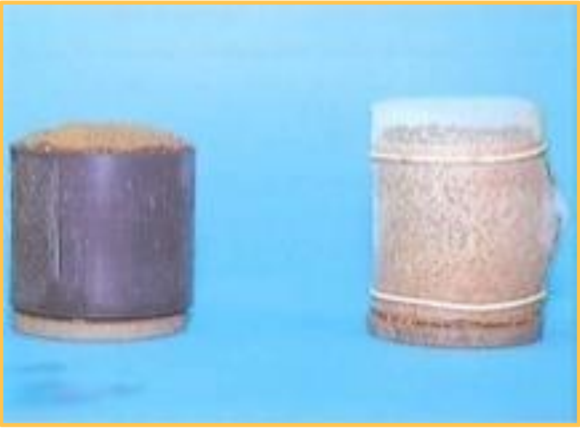
The decision to carry on with the "treatment" solution depends on the particular context of the site.

The values proposed in this table are the result of recent experience and may be adjusted in the future in the light of the elements brought by the generalisation of the practice of the test.

***Test to assess the suitability of a soil for treatment with lime and/or hydraulic binders***

### Reference GTS

Detail of two specimens. Left specimen kept in its steel container is used to evaluate the progress of the hydraulic set. The specimen with wesh wrapping is used to measure volume swelling.



*Picture 28: Test to assess suitability of a soil for treatment with lime and/or hydraulic binder (detail)*

Both specimens in temperature controlled bath.

*Picture 29: Specimens in temperature controlled bath of the suitability test*

Note that the Rtb diametral compression test (more commonly known as the "Brazilian type tensile test") corresponds to standard NF P98-232-3 (European standard EN 13286 part 42).

Other swelling thresholds should be considered, particularly in Europe.

**See References Europe in Appendices 3 and 4**

## 6.5. MIX DESIGN STUDY

### 6.5.1. General methodology of mix design study

***Importance of the site***

As we pointed out in § 6.2.2, the cost and time required for a mix design study is often prohibitive for small construction sites. It is, however, possible not to give up the soil treatment solution by empirically fixing the type of treatment product and its dosage according to the soil class, as indicated in table 7.

For sites that cannot be considered as being of minor importance in the sense defined above, a formulation study is required.

***The different levels of mix design study***

The level of the formulation study adapted to a given site is mainly defined by the following factors:

- the level of experience acquired on similar sites,
- the economic interest of optimising the dosage.
- the way in which the shape layer is taken into account in the design of the pavement.

Depending on the answers that can be made to each of these factors, a mix design study at different levels is conducted to meet increasing performance objectives when it is possible to achieve them.

The mix designs are based on the following elements in § 6.5.2.

### 6.5.2. Basic elements of a mix design study

***Identification of the components of the mixture***

**Soil to be treated**

The soil to be treated is identified according to the parameters of nature and moisture state used for soil classification, completed, if justified, by measuring fragmentability and abrasiveness (see Tests methods in the booklet "2D / Earthworks execution and controls" of the Earthworks Manual).

**Binders**

Lime and/or cement are identified and tested on the basis of the criteria defined in the corresponding standards (or possibly on the basis of the technical data sheets of the producers).

For **HRB**, the identification is established on the basis of the main characteristics contained in the technical notice or, failing that, in the technical data sheet of the producer.

**Water**

The water introduced must comply with the standard in force or after justification by a specific study.

***Choice of treatment products and dosages***

The choice is made on the basis of experience of soil behaviour with locally used treatment products.

The dosage of treatment product(s) is expressed as the ratio of the mass of treatment product to the mass of the solid constituents of the mixture (including the treatment product).

***Processing characteristics of mixtures***

The aim is to estimate the behaviour of the material during its implementation and to determine the compaction references ($W_{OPN}$ and $\rho_{dOPN}$) of the treated soil.

This is done by establishing the Proctor Normal curves of the soil before and after treatment and the IPI curve of the treated soil.

The study is conducted on samples prepared at various water contents (at least five recommended).

## Reference France (GTS application)

**Figure 9** shows an example of a representation of a Normal Proctor - IPI study to be carried out for the determination of the processing characteristics of treated soils for a capping layer. In this case, it is the case of a class A2 silty soil (see GTR Synoptic figure 7).

The water contents noted $w_{i1}$.... $w_{i5}$, include the range of natural water contents wn representative of the work season.

After performing the Proctor compaction and immediate punching test (IPI), the final water content wf and the dry bulk density of each specimen are determined.

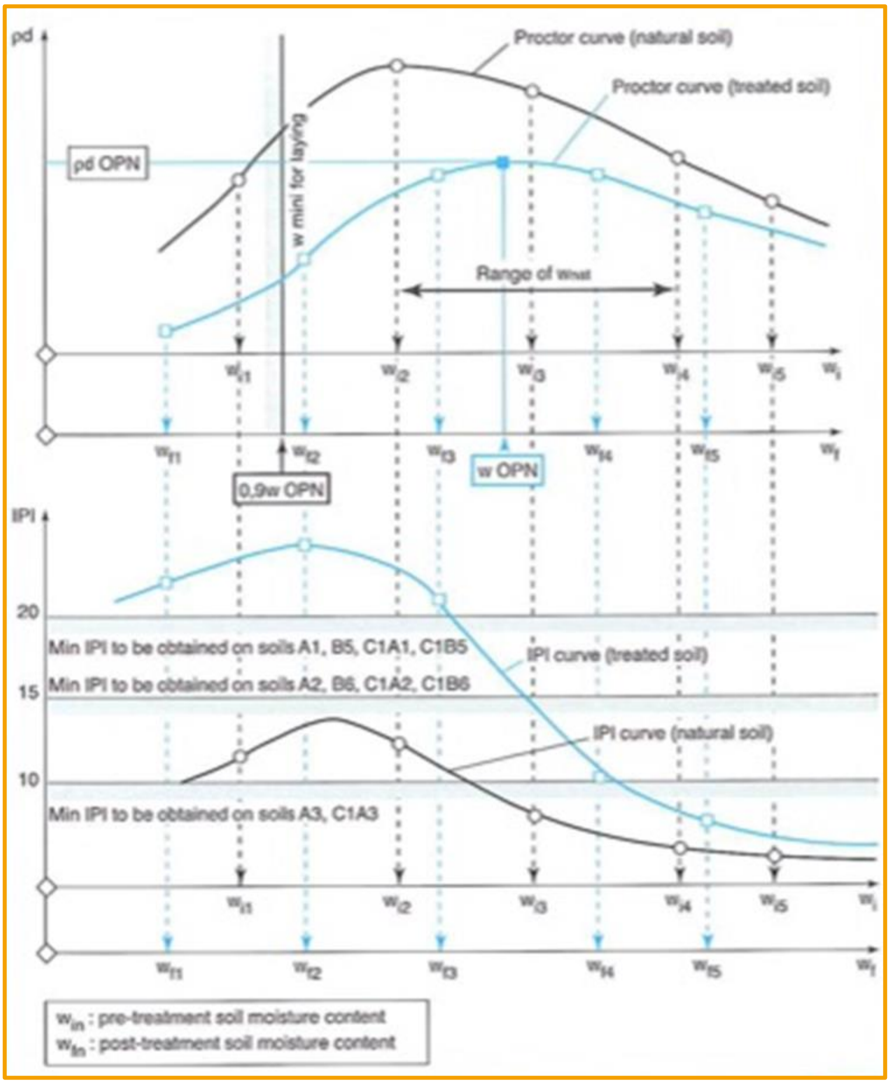



*Figure 9: Example of presentation of a Normal Proctor-IPI study*

Example of a representation of a Proctor Normal-IPI study to be carried out to determine the implementation characteristics of treated soils for capping layer (case of an A2 soil treated with 1% CaO + 4% CPJ-CEM II/A 32.5).

The processing characteristics of the mixes to be used on the construction site must meet the following two conditions

**The immediate bearing index (IPI)** measured on the treated soil from the prepared sample at wi = wmax of the wnat range, must be at least equal to IPI values determined according to the class of material.

Example of the values proposed in the case of the GTS in Table 11:

| Material class | Minimum IPI |
|---|---|
| $A_3$ - $C_1A_3$ | 10 |
| $A_2$ - $C_1A_2$ - $B_6$ - $C_1B_6$ | 15 |
| $A_1$- $B_5$ - $C_1A_1$ - $C_1B_5$ | 20 |
| Other materials | Set from experience or from specific study |

*Table 11: Minimum Immediate Bearing Index (IPI) to be achieved during implementation*

In the example in Figure 9, the IPI to be considered is the one corresponding to $w_{i4}$ after treatment.

**Reminder Soil classes (reference GTR France)**

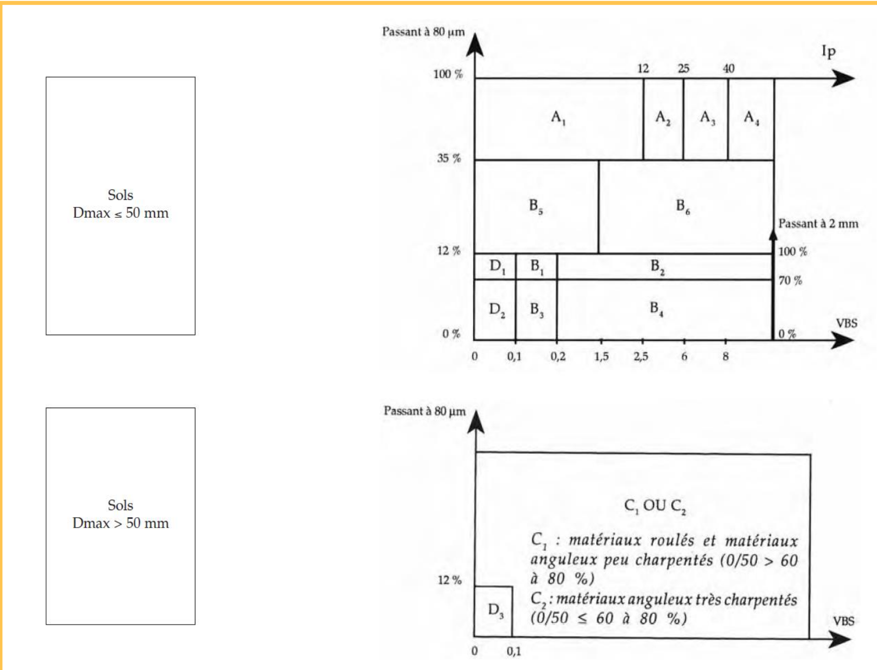



*Figure 7: GTR Material classes*

The final moisture content ($w_f$) of the treated soil from the prepared sample at wi = wmin in the wnat range must be greater than or equal to 0,9 $w_{OPN}$ of the treated soil.

In the example in Figure 9, this is the case for $w_n$ values greater than or equal to $w_{i2}$ because, after processing, $w_{i2}$ becomes $w_{f2} > 0.9\ w_{OPN}$.

If the foreseeable range of wn during execution does not allow these conditions to be met for a significant part of the soil to be treated, consideration should be given to the need to either moisten the material in its mass or, conversely, to aerate or treat with quicklime (or increase the lime dosage in the case of double treatment). These eventualities will have to be assessed from a technical and economic point of view.

***Determination of the workability period***

When soil treatment is carried out with a hydraulic binder (Cement or HRB), it is important that a certain number of elementary operations of implementation are carried out within the workability period.

The determination of the workability period is carried out according to the methodology described in standards or guides in force.

For the majority of construction sites, a value of four to six hours is satisfactory at 20° (at 30° the values are divided by 2). Higher values may be sought, if justified by particular site organisation conditions.

It should be noted that hydraulic road binders (HRB) produced in some countries allow for more favourable workability periods than conventional cements.

***Mechanical performance study***

There are two types of treatment to consider:

- Lime treatment only
- Treatment with hydraulic binders possibly associated with lime

***LIME TREATMENT ONLY***

This type of treatment is generally only considered for fine soils with medium to high clay content (PI > 20) and in areas with little or no frost.

Moreover, current experience shows that this type of treatment limits the platform class obtained (e.g. France class PF3).

***Mechanical characteristics study***

The evolution of mechanical performance is too slow to be able to set $\mathbf{R_t}$ or $\mathbf{R_{tb}}$ values representative of the long term.

The mechanical characteristics to be considered for a lime treatment are the following.

- **For the study of behaviour under traffic:**

  Reference should be made to **IPI** and $\mathbf{I_{CBR}}$ values after 4 days of immersion carried out on two samples of treated soil compacted with Normal Proctor energy and to the two water content values delimiting the range of water contents allowing its correct implementation.

Judging Criterion:

The following two conditions must be checked for the two water contents under consideration and the corresponding lime dosages:

$$\boxed{I_{CBR} \geq 20 \text{ and } I_{CBR} / IPI \geq 1}$$

With $I_{CBR}$ measured after four days of soaking

- **For the study of frost behaviour, if applicable**

Unconfined compressive strength **($R_c$)**, tests, carried out on specimens 10 cm high and 5 cm in diameter, statically compacted at **$W_{OPN}$ and 98,5 % of the $\rho_{dOPN}$** of the mixture and kept for a period of time representative of the time between the end of the work and the probable date of frost on the site in question (refer to Appendix 6. for a reference on how to prepare the specimens).

The values used for interpretation are the average of at least three measurements.

Judging Criterion:

Where there is a risk of frost penetration into the subgrade, the compressive strength of the treated soil at the age corresponding to the probable date of onset of frost at the worksite in question shall be checked to ensure that the condition is complied with:

Compressive strength $\boxed{R_c \geq 2{,}5 \text{ MPa}}$

Conditions of application:

The reason why an unconfined compressive strength was chosen for soil-lime mixtures (preferably to a diametral compressive strength) is due to the relatively low short and medium term stiffness of these materials, which does not allow a correct interpretation of a diametral compression test.

The minimum value of Rc is to be used under the following conditions.

Treatment with lime alone is generally not recommended when the age of the treated soil is less than three months (90 days) at the time of possible frost occurrence.

If the results of a specific frost heave study, based in particular on frost heave tests (1), are available, these shall prevail over the strength value indicated.
(1) Reference France made according to the NF P 98-234-2 standard

It should also be noted that the risks of heave by cryosuction are only really significant when the materials have the possibility of being in a saturated state at the time of freezing.

***TREATMENT WITH HYDRAULIC BINDERS POSSIBLY ASSOCIATED WITH LIME***

We consider here the HRB, hydraulic binders which seem to us to be the most suitable for the treatment under consideration.

***Representative mechanical characteristics and judging criteria***

The mechanical characteristics to be taken into account are:

- The unconfined compressive strength $\mathbf{R_c}$
- The tensile strength $\mathbf{R_t}$ or the indirect tensile strength $\mathbf{R_{tb}}$

  $\mathbf{R_{tb}}$ diametral compression test (more commonly known as the "Brazilian type tensile test")

  ($\mathbf{R_t}$ = 0,8 $\mathbf{R_{tb}}$ can be assumed)
- The modulus of elasticity **E**

The behaviour of the treated soil is to be assessed by means of criteria for judging:

- the age at which the treated layer can be driven on
- resistance to immersion at an early age
- frost resistance
- the performance expected in the long term.

Table 12 proposes representative mechanical characteristics for the various aspects of the behaviour of the treated material. Judgement criteria are to be determined. The thresholds for these judging criteria may vary from country to country.

The example of the French practice (GTS) is shown in this table.

## Reference France and Europe

**TABLE 12: Requirements for the mechanical characteristics of soil treated with a hydraulic binder / Basic study**

| Aspect of treated soil performance considered | Representative mechanical characteristics ● | Criteria for judgment |
|---|---|---|
| Age at which traffic can be allowed on treated soil considered | $R_c$ at 7 days and $R_c$ at 28 days (one measurement of $R_c$ at 2 or 4 days may beneficially be considered in case of relatively fast setting binder and/or when construction is to take place in fine weather) | The capping layer can be opened to traffic when $R_c$ > 1 MPa ✪ The age at which this condition is met is obtained by interpolation between $R_c$ values measured at 7 and 28 days (or between values at 2 or 4 days and 7 days if applicable) |
| Resistance to immersion at young age | $R_c$ after 28 days normal curing followed by 32 days total immersion in water at 20°C ($R_{ci}$) $R_c$ after 60 days normal curing ($R_{c60}$) | Resistance to immersion at a young age is considered satisfactory if $\frac{R_{ci}}{R_{c60}} \geq 0{,}80$✪ (when $VB_s$ of soil is < 0.5) or $\frac{R_{ci}}{R_{c60}} \geq 0{,}60$✪ (when $VB_s$ of soil is > 0.5) |
| Resistance to frost | $R_t$ or $R_{tb}$ at age of treated soil on probable onset of freezing weather at site considered ✧ | Frost resistance is considered satisfactory if the $R_{tb}$ at the age corresponding to the first statistically possible onset of frost is greater than 0.25 MPa [13] ◆ |
| Expected long term performance | $R_t$ or $R_{tb}$ and elastic modulus E measured at 28 and 90 days and if necessary 180 days in case of slow setting hydraulic road binder HRB. | The ($R_t$, E) pair determined at 90 days (or 180 days in the case of a slow setting binder) produces at least a material of mechanical class 5 determined by application of figure C1-4 and table C1-X ● |

● All the characteristic values mentioned above are averaged over at least three measurements
✪ This is a target value for average sized jobs. Slightly higher or lower values may be more suitable in certain special contexts
✧ To be determined from statistical data from national meteorological office [38, 39, 40]. As a first approach, guidance may be sought in LCPC technical note entitled Grassing of Road Rights of Way: Determination of Periods when Grassing is Banned, October 1974.
◆ This value is adopted in the light of current knowledge. It can be considered as an envelope value ensuring good frost performance (against swelling and cracking) of the treated materials (except for chalks for which confirmation is still needed). If results are available from a special frost swelling study based on frost swelling tests performed by the method described in French Standard NF P 98-234-2, they take precedence over the resistance value shown. Lastly, it must be remembered that risks of swelling from cryosuction are greater in favourable weather and when water has access to the capping layer material (in cuts, especially when poorly drained). For these reasons, the value of 0.25 MPa may be increased (to 0.3 MPa for example) or may be ignored (sufficiently low probability of frost or non freezing natural soil)
● Mechanical class considered in GTR capping layer design tables

*Table 12: Requirements for the mechanical characteristics of soil treated with a hydraulic binder / Basic study*

**Performance classes**

It is desirable to define performance classes for the design of subgrade layers, such as for pavement base layers made of treated soils.

**Classification of materials according to couple $R_t$ / E**

The establishment of grading zones for the treated material according to couple $R_t$ / E allows to define mechanical performance classes.

The mechanical class obtained makes it possible to predict the optimum use of the capping layer in the pavement structure.

## Reference France and Europe

### European Standard Reference (see Appendix 5)

The figure 10 gives classification areas of the treated material according to the tensile strength $R_t$ ($R_t$ = 0.8 $R_{tb}$) and the elastic modulus E of the treated material. The mechanical classes 1 to 5 correspond to the areas of the graph. (*)

The couple (**$R_t$ / E**) determined at 90 days (or possibly at 180 days in the case of slow-setting binder) leads to at least a material of mechanical class 5 determined by application of figure 10.

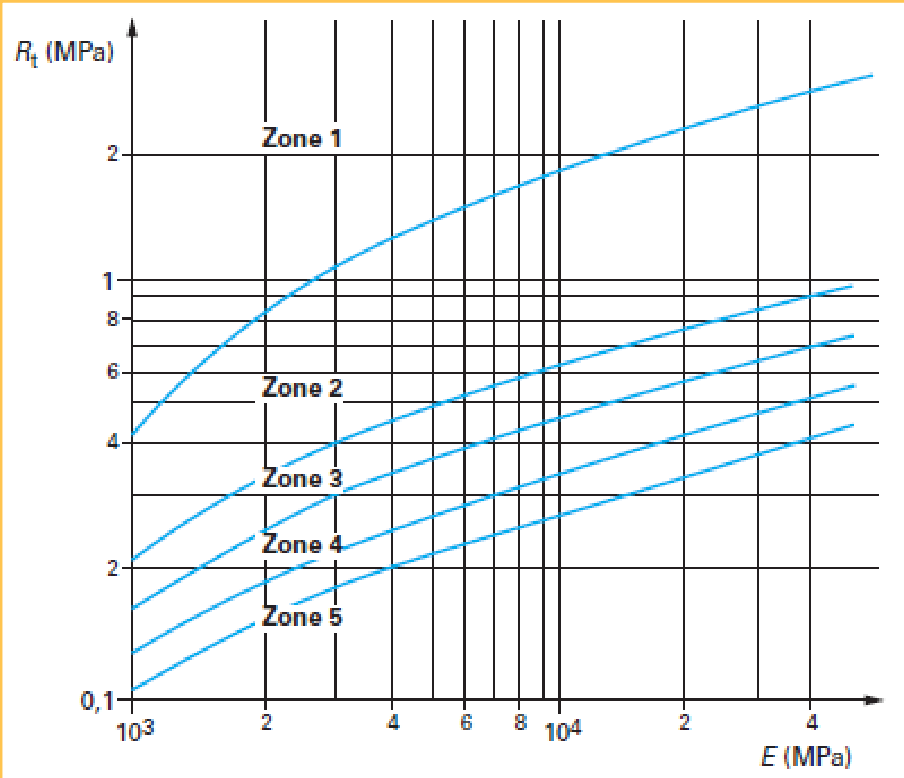



*Figure 10: Classification zones of the material as a function of its tensile strength Rt and modulus of elasticity E*

When the study was conducted using diametral compression tests, $R_t$ is evaluated from the relationship: $R_t = 0{,}8\ R_{tb}$.

The E-modulus is determined either from a direct tensile test (Reference France standard NF P 98 232-2), or from a diametral compression test (Reference France standard NF P 98 232-3) using, as far as possible, a special device for measuring the diametral deformation, i.e. the deformation of the specimen diameters during the compression test using measuring extensometers. (Reference European standard: EN 13286 Part 40)

**Basic tests for evaluating the mechanical strength of soils treated with hydraulic binders**

The two basic tests for evaluating the mechanical strength of soils treated with hydraulic binders are as follows:

- Unconfined compressive strength measurement (on specimens with slenderness 2) to characterize short-term behavior.

*Picture 30: Measurement of the unconfined compressive strengtht*

- Measurement of diametral compressive strength and tensile modulus to characterize long-term behavior and to design the structure

*Picture 31: Measurement of the diametral compressive strength*

The study shall be carried out on specimens whose dimensions and methods of compaction are given in Appendix 6.

The mixing of the soil is carried out according to the methods described in standard NF P 98-093, using in particular the mixer-disintegrator described in the informative appendix of this standard.

*Picture 32: Disintegrating mixer - Detail of the mixer (GTS)*

*Picture 33: Disintegrating mixer - Detail of the mixture obtained (GTS)*

(*) The GTS foresees a different correspondence between zone and mechanical class depending on the processing mode, in plant or in place (see Table 13).

As noted in the paragraph on treatment equipment, advances in existing treatment equipment may call this difference into question.

| Treatment in stabilisation plant* | In-place treatment | Mechanical class of material |
|---|---|---|
| Zone 1 | | 1 |
| Zone 2 | Zone 1 | 2 |
| Zone 3 | Zone 2 | 3 |
| Zone 4 | Zone 3 | 4 |
| Zone 5 | Zone 4 | 5 |

* This method of preparation can only be considered if one can be sure that the material can flow correctly through the plant (soil classes B, D, and certain class A soils pretreated with lime)

*Table 13: Determination of mechanical class of treated material on the basis of its characteristics and method of preparation*

### 6.5.3. Different levels of the mix design study according to the objectives

***General***

Three levels of mix design studies of increasing scale can be envisaged:

- First level study to verify the adequacy of the performances obtained with the objectives set.
- Second level study which includes the determination of the binder dosages and the optimization of the performances to be achieved.
- Third level study which concerns the design of capping layers according to the pavement structures calculation.

**GTS reference**

Refer to the flow chart in Figure 11

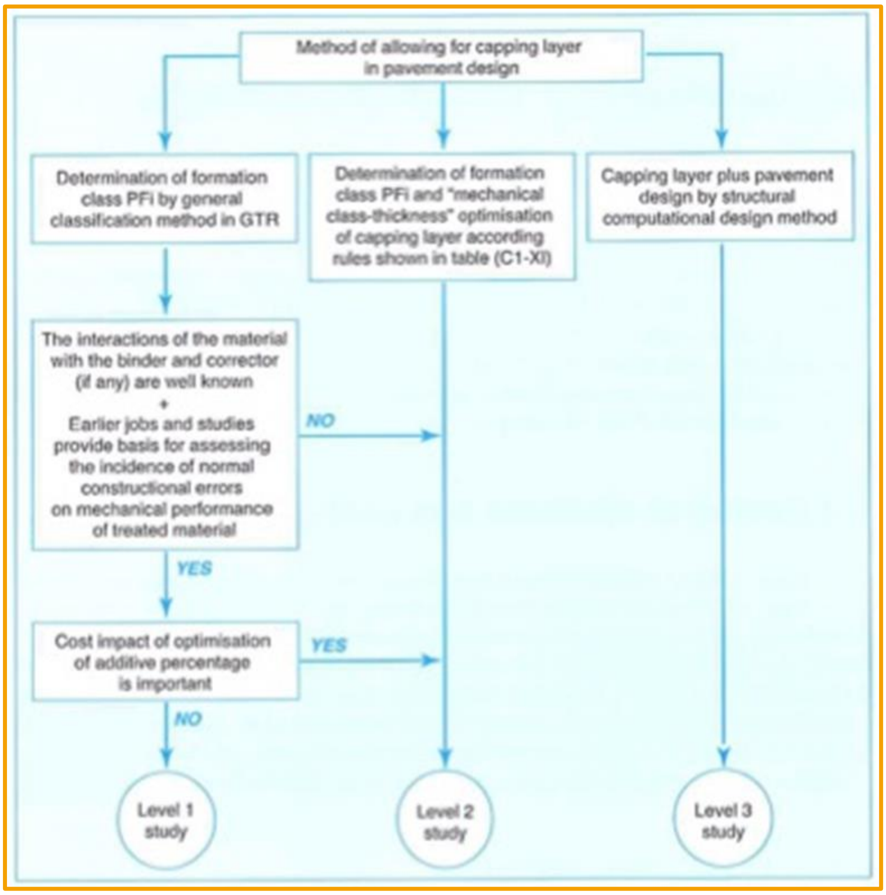



*Figure 11: Flowchart showing the level of formulation study to be undertaken*

***First level study***

__Objective__

The level 1 mix design study corresponds to the verification by the basic study that the composition, chosen a priori according to experience (called the "basic formula"), enables the desired level of performance to be achieved in the short and long term the mechanical characteristics (see § 6.5.2).

Feedback includes the following points:

- The interactions of the material with the binder and the possible corrector are well known.
- Previous studies and worksites make it possible to evaluate the impact of current execution variations on the mechanical behaviour of the treated material.

In this first level of study, the method of taking into account the capping layer in the design of the pavement is based on the determination of the class of formation level obtained, according to the general classification method used in the country (for example, in France PFi classes in the GTR Guide).

**Note**

Where the treatment envisaged is a double treatment (lime + hydraulic binder), the basic formula under consideration must fix both the lime and binder dosages.

If it turns out that the lime dosage is likely to vary significantly (> two points of lime) during the execution of the work to correct the moisture state of the soil, it is recommended to undertake a first level study for the minimum and maximum values of the lime dosages that can possibly be applied.

**Study inconclusive**

If the targeted performance is not achieved, it must be concluded that the experience that led to the choice of the basic formula was not sufficient and a second level study will have to be performed.

***Second level study***

The level 2 mix design study consists of a level 1 study (baseline study) plus a study of the impact of dosage, moisture content and compactness on the performance of the mixture.

**Objectives**

**Additional study objective for the desired performance**

Firstly, a level 2 mix design study should be initiated when the level 1 study has not been able to confirm the level of performance expected a priori, in particular for the following reasons:

- the interactions of the material with the treatment product are poorly known. This will involve optimising the dosage(s) of treatment product(s).
- The impact of common variations during execution on mixture behaviour is poorly known. It will be a question of defining the modalities of adjustment of the dosage of binder allowing to correct them.

**Optimization objective**

This is the main interest in initiating a second level study:

- Cost-effective optimisation of the dosage and of the "mechanical class of the treated soil" / thickness of the subgrade

It is a question of determining the dosage of treatment product leading to a material whose mechanical characteristics (Cf Mechanical Classes / couple Rt / E of figure 10) allow, for the class of subformation level under consideration and the thickness of the envisaged capping layer, to reach the classes of formation level proposed in table 14.

The knowledge of the mechanical class of the treated material and of the subformation level class allows the design of the treated capping layer, according to the targeted formation level.

These different criteria are listed in Table 14 **(GTS reference)**.

| Mechanical class of capping layer material | Capping layer thickness | | | | |
|---|---|---|---|---|---|
| | Sub-formation class AR1 | | | Sub-formation class AR2 | |
| Class 3 | • | 30cm | 40cm | 25cm | 30cm |
| Class 4 | 30cm | 35cm | 45cm○ | 30cm | 35cm |
| Class 5 | 35cm | 50cm○ | 55cm○ | 35cm | 45cm○ |
| Formation class obtained | $PF_2$ | $PF_3$ | $PF_4$ | $PF_3$ | $PF_4$ |

• Because of the significant contrast in moduli, building a capping layer with treated material of class 3 on an AR1 sub-formation is not permitted below a thickness of 30 cm

○ Obtaining the required bottom-of-layer density generally calls for two layers construction

*Table 14: Platform class according to the AR thickness class, the mechanical performance of the treated material and the thickness of the form layer*

<u>Note</u>

Please note that the interpretation of this table must be associated with the frost penetration analysis which may lead to an increase in the proposed thicknesses.

**<u>Consistency of the study</u>**

The study is carried out on the basic elements described in the paragraph 6.5.2.

The specific modalities for the level 2 study concern the following aspects.

**The identification of the components of the mixture and the choice of the treatment product**

Only hydraulic binders (cement and HRB) possibly associated with lime are considered here. The proposed methodology cannot be applied to the type of lime treatment alone if there is not enough experience on the behaviour of treated soils; it could only be applied as a first approach.

**The study of the implementation characteristics and the workability period**

These operations are carried out as described in the paragraph 6.5.2 for the level 1 study.

If the range of dosage values studied does not exceed three points (the most frequent case and the only one described here), only one Proctor-IPI study can be carried out, which is then carried out on the mixture with a binder dosage that can be considered most likely for the soil, binder and performance level considered.

**The study of the evolution of the mechanical performances $R_t$ (or $R_{tb}$) and E as a function of the dosage**

This study is carried out for at least two values of the binder dosage. The methods of moulding the specimens are the same as in the level 1 study.

**The study of the early behaviour of the treated material**

This study makes it possible to evaluate the suitability of the treated material to be put back into circulation as well as its resistance to immersion and freezing. For this purpose, the dosage taken into account for the Proctor-IPI study indicated above is used. For the formula corresponding to this value, the different characteristics $R_c$ at 7 or 28 days, $R_{ci}$, $R_{tb}$, defined in the basic study, are measured.

**The study of the sensitivity of the mechanical behaviour of the treated soil with respect to the variations of dosage, compactness and water state foreseeable in the context of the construction site**

The purpose of this study is to quantify the effects of execution variations on mechanical performance and to assess the extent to which they can be compensated for by adjusting the binder dosage.

It is conducted on the formula used for the Proctor-IPI study.

The $R_{tb}$ **(or $R_t$)** is measured at 90 days (or 180 days in the case of slow setting binders) obtained on specimens of the same dimensions as those used for the study defined in § 6.5.2 and made up according to the procedures indicated in the table below:

| Influencing parameters | Additive percentage | Unit weight | Moisture content |
|---|---|---|---|
| Additive percentage and density | 90% of basic formulation percentage | 94% $\rho d_{OPN}$ | $w_{OPN}$ |
| Additive percentage and moisture content | 90% of basic formulation percentage | 96% $\rho d_{OPN}$ | 0,9 $w_{OPN}$ and 1,1 $w_{OPN}$ |

*Table 15: Methods of specimen preparation for the sensitivity study of the influencing parameters*

***Third level study***

<u>**Consideration of the capping layer in pavement design**</u>

The use of the capping layer in the the pavement design is a source of savings for the project and promotes the optimal use of natural materials.

The process proposed as an example is that of France (GTS Guide).

**Important preliminary remark**

The approach is appropriate for large projects, for which certain specific conditions can be met, in particular the availability of detailed surveys, sufficient time for mix design studies and efficient means of execution. The quality assurance actions must also allow a clear validation of the results of the mix design study based in particular on measurements on cores and have foreseen the possible possibility of correction of the project in the light of the results obtained.

**Objective**

A level 3 study is to be carried out, as shown in Figure 11, when a design of the couple "capping layer - pavement structure " using a calculation method is envisaged (e.g. France "Alizé" model).

The objective of the study is then to determine, for different mix designs, the mechanical characteristics $\mathbf{E_t}$ and $\mathbf{R_t}$ that can be introduced into the calculation model, in order to retain those leading to technical and economic optimisation of the pavement.

The interest of such an approach is particularly justified for large construction sites. It requires:

- geotechnical survey and mix design studies of sufficient detail to reliably assess the values of the modulus of the soil to be entered into the design model and the targeted level of mechanical performance for the capping layer material,
- a control of the consistency of the execution conditions with the level of variation taken into account in the study, on the basis of a suitability test.
- the execution of the construction site in accordance with the conclusions of the suitability test,
- the establishment of a quality assurance system providing in particular for the control of the mechanical characteristics obtained on site, carried out on cores and/or by ovalisation measurements and representing a statistically representative population.

**Consistency of the study**

The study is carried out on the basic elements described in the paragraph 6.5.2.

The specific modalities for the level 3 study concern the following aspects.

**Identification of the components of the mixture**

The identification of the components of the mixture shall be carried out as described in section 6.5.2.

The study of the implementation characteristics and the workability period

This study may require several Proctor-IPI studies, as it is likely that the range of dosages to be explored exceeds three points.

**Behavioural studies (early immersion and frost resistance)**

This study must be carried out for each of the Proctor characteristic values determined from the implementation characteristics study.

**Determination of the values of $E_t$ and $R_t$ and study of the sensitivity of these parameters to execution variations**

We determine the values of $\mathbf{E_t}$ and $\mathbf{R_t}$ as well as the sensitivity of these parameters to execution dispersions for the mixtures that are considered to be the most interesting to achieve the desired optimization. The sensitivity study shall be carried out as in the case of the level 2 study on specimens manufactured according to the procedures proposed in the basic elements.

For each of the mixtures studied in this section, the values of the couple (**$E_t$** ; **$R_t$**) to be introduced into the calculation model are those that proved to be the most unfavourable at the end of the study of sensitivity to execution variations.

**Interpretation**

For each of the mixtures studied in part 4, the values of the couple (**$E_t$** ; **$R_t$**) to be introduced into the calculation model are those that proved to be the most unfavourable at the end of the study of sensitivity to execution variations.

These values must, moreover, be obtained for **dosages guaranteeing good behaviour during execution, as well as immersion and freezing** as defined in § 6.5.2 or that it can be accepted that they will be obtained by adopting, at the time of the works, special provisions tested and validated by the suitability test.

For paragraphs 5 and 6, please refer to **Appendix 6:** Dimensions and method of manufacture of test pieces

# 7. CARRYING OUT EMBANKMENT TREATMENTS

## 7.1. THE APPLICATIONS CONSIDERED

We have seen this previously, the main purpose of soil treatment applied to embankments is to allow the reuse of water-sensitive soils that are too wet (or possibly too dry) at the time of extraction, to ensure trafficability and to be able to be implemented under acceptable technical and economic conditions.

Treatment may also be considered for certain parts of the fill, requiring materials with mechanical characteristics superior to those of common backfill bodies.

We will distinguish the execution of treatments for the categories of works:

- common embankment bodies
- specific embankments (technical areas)
- TSE

Appropriate techniques, depending on the nature and water status of the soil, have been described in § 3 of this present booklet:

- **Lime treatment alone** is most often used for standard backfill
  - to lower the moisture content of materials that are too wet,
  - to allow the treatment of materials that are too dry (in the form of milk of lime)
  - sometimes to increase the mechanical characteristics of the materials,
- **Treatment with hydraulic binders** (cement, HRB, etc.) mainly concerns specific fillings
- **Double lime-hydraulic binder treatment** also mainly concerns specific embankments for materials that require prior lime treatment

## 7.2. TREATMENT IN ITS APPLICATION TO THE REUSE OF EXCESSIVELY WET SOILS

Most commonly applied for the construction of common embankment bodies.

The **most suitable treatment product** is usually calcium air lime in the form of quicklime.

The parameter used at the study stage to decide on the need for treatment and the dosages to be applied is **the Immediate Bearing Index (IPI)** of the soil at its probable moisture content at the time of application;

The decision to carry out a soil treatment most often has a significant impact on the economics of the site

This aspect requires detailed **geotechnical and economic studies** to compare the costs of alternative solutions.

### 7.2.1. Execution materials

Reference should be made to the Part 2D of the Manual with the following specific modalities.

***Soil preparation***

In general, no special soil preparation is required for this application, with the exception of low-density, wet or very wet chalk, which may benefit the productivity of the mixing plant.

If the presence of big elements poses mixing problems, the solution lies more in finding a suitable execution technique rather than in modifying the granularity of the soil.

Case of "coarse" materials with Dmax > 100 to 150 mm:

- disposal by sorting (manual or mechanical shovel) or by screening
- reduction by crushing
    - in place
    - with mobile installation

*Picture 34: Site preparation worksites (Photos Guintoli – NGE)*

***Spreading equipment***

Important aspects to consider when choosing a spreader are:

- the consistency of its productivity in relation to that of the entire earthmoving workshop
- the difficulties in circulating on the soil, generally encountered by spreaders in applying the treatment to the reuse of too wet soil (often a critical phase for the treatment site).

*(photo Techniques de l'Ingénieur)*

*(photo RAZEL)*

*Picture 35: Binder spreading sites*

| Valeurs indicatives | CHARRUE | | PULVI-MIXER (arbre horizontal) | CENTRALE |
|---|---|---|---|---|
| | à disques | à socs | | |
| **Caractéristiques** | nombre de passes - vitesse | | finesse de la mouture | - précision des dosages<br>- homogénéité du malaxage |
| **Epaisseur traitée** | 0,15 à 0,20 m | 0,30 à 0,50 m | 0,35 à 0,45 m | |
| **Limites** | D < 250 à 350 mm | | D < 100 à 150 mm | D < 50 mm - IP < 12 |
| **Traitement** | LHR ou chaux | | LHR ou chaux / LHR | |
| **Destinations** | RO et pré-traitement | | Remblais techniques – CF – Chaussées | |

*Different mixing methods (Photo NGE)*

*Dourges jobsite France (Photo Razel)*
*Picture 36: Binder Mixing Plants*

***Mixing machines***

For materials intended for common embankment bodies, disc or ploughshare ploughs are the most suitable mixing equipment (technically and economically) for soil treatment for the purpose under consideration here.

This equipment can mix materials up to a grain size of 0/300 mm and a depth of about 50 cm.

The quality of mixing and aeration produced by ploughs can be improved by loading-transport-unloading machines such as scrapers when the transport cycle is adapted for these machines (especially self-loading scrapers when this equipment is used).

Large horizontal shaft soil pulvimixers may be used in soils whose granularity allows them to be used, provided that they can justify a cost saving compared to ploughs (taking into account the saving in the dosage of the treatment product).

The pulverisers are suitable for materials such as chalk and marl, clayey pelites to reduce the granulometry and obtain a correct grinding (fractionation to obtain 0/20 mm, 0/40 mm or 0/60 mm).


*Development of the mine of CARMAUX France (Photo GTM)*
*Picture 37: Treatment in the cut with a plough (1)*

*Motorway A 89 France (photo Razel)*
*Picture 38: Treatment in the cut with a pulvimixer (2)*

*Motorway A9 Montpellier France (Photo VINCI Construction Terrassements)*
*Picture 39: Treatment on the fill*

***Compaction equipment***

These are the machines used for compacting embankment bodies.

Note the efficiency of a Tamping type compactor especially for materials such as chalk and marl, very plastic clays (A3, A4).

Tamping allows the material to be "Kneaded".

### 7.2.2. Construction techniques for treatment of materials for embankments

***Common technique***

The treatment applied to the reuse of water-sensitive soils that are too wet is almost always carried out by "in-place" treatment. The common technique consists in spreading the mass of treatment product, calculated for the intended mixed soil thickness, and mixing it with the soil, usually with the help of ploughs (disc or share ploughs) - as mentioned above - until a homogeneous appearance (colour and "grind") is obtained. Then, depending on the case, the mixture is either loaded and transported to the place where it is to be used (excavation treatment) or compacted directly after mixing (backfill treatment).

Different modalities, described below, may sometimes be necessary to adapt to the particularities of certain worksites.

***Mixing by the technique known as "deposition-recovery"***

This technique allows mixing soils with blocky elements of Dmax > 250 to 350 mm (value considered as a practical limit for mixing with ploughs). However, it is reserved almost exclusively for treatment with lime because it is incompatible in principle with the phenomenon of hydraulic setting.

It is performed as follows (Fig. 12-B).

The quantity of treatment product corresponding to the chosen dosage, calculated for the thickness of the layer to be removed, is spread on the soil. The combination of the material of this layer and the spread treatment product is loaded, transported and then placed in temporary storage. It is profiled and lightly compacted to minimize rainwater ingress. At the appropriate time (which may be several days, weeks or even months later), the deposit is taken up again, in frontal extraction, to make the backfill.

This technique improves the homogeneity of the excavated soil (in nature and state) while at the same time producing a mixture of generally sufficient quality for backfilling, without using specific mixing equipment.

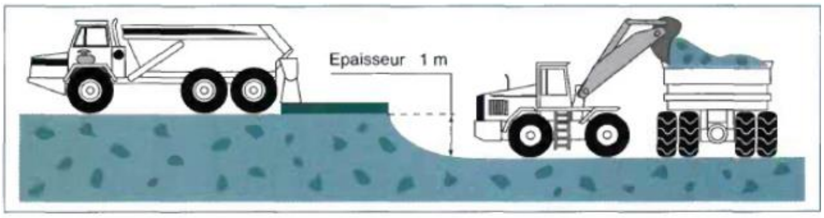
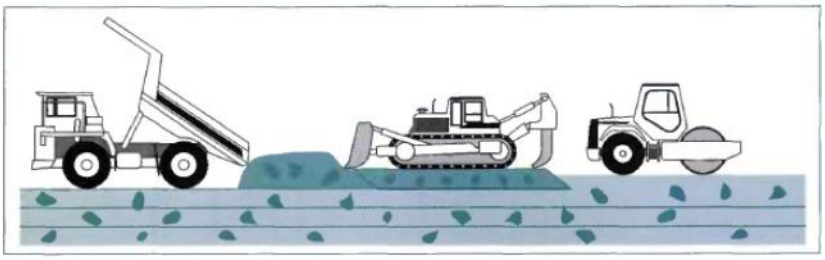
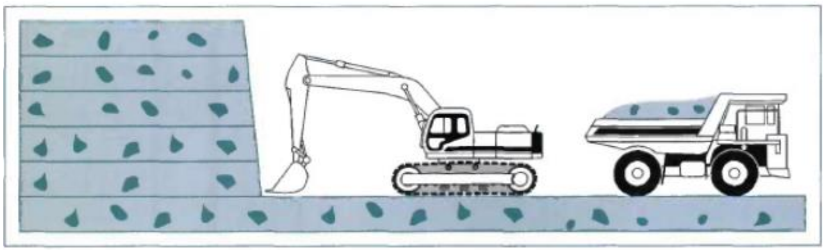
| | |
|---|---|
| **A** |  |
| **B** |  |
| **C** |  |

*Figure 12: Principle of the mixing process using the deposition-recovery technique*

**A** - Spreading of the quantity of treatment product corresponding to the targeted dosage and the thickness of material extracted and loaded.

**B** - Constitution of the temporary storage area: unloading, levelling, light compaction of each elementary layer and closure of the surface platform (in the case of soils sensitive to segregation, it is advantageous to unload the mix on the layer being levelled and push it in front of the levelled layer).

**C** - Recovery of the deposit by frontal extraction achieving a good homogenization.

***Mixing technique specific to low to medium density wet chalk***

This class of chalk has a specific behaviour due to its porous (therefore friable) saturated or near saturation structure. During the earthmoving operations, a fine matrix is produced, the greater the brittleness, the more important it is, and the higher the water content of the chalk in place, the less consistent it is.

As soon as the proportion of the matrix exceeds values of 5 to 10%, it communicates its behaviour to the whole material. To be able to reuse these materials as fill, it is therefore not necessary to reduce the water content of the chalk mass, but only that of the matrix produced during the work.

This can be achieved as described below.

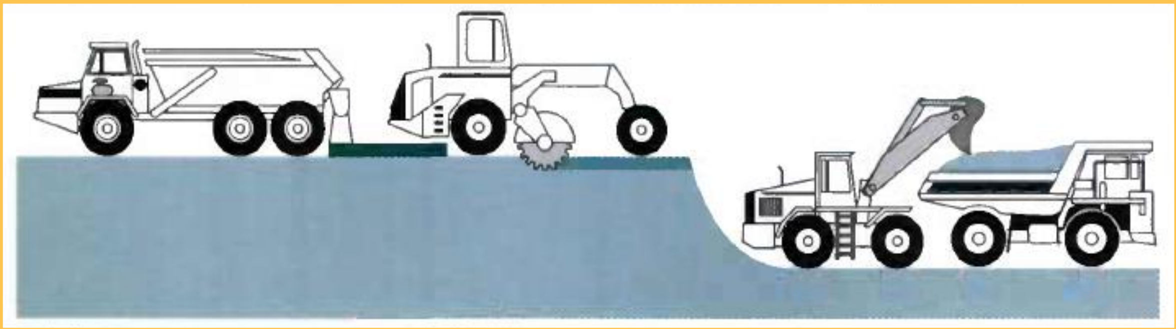


*Figure 13: Treatment technique specific to the reuse in backfill of friable chalk that is too wet (classes R12 and R13h)*

The chalk is treated in its mass, to the thickness allowed by the mixing machine used, seeking during this operation a maximum production of fines. A 0/20 mm grind should be aimed for and a horizontal shaft mixer should be used wherever possible. The dosage of the treatment product, particularly in the case of quicklime, must be high enough to ensure that the matrix produced is in a dry powdery state (search for an **IPI on the 0/20 mm grind > 20).**

The layer thus treated is then extracted simultaneously with a layer of chalk in place (about one meter thick), using loaders or shovels to avoid excessive destructuring of the material in place, and thus additional production of matrix that would have to be dried. The thickness of the layer to be extracted is adjusted according to the observation of the behaviour of the material during backfilling (if it retains a high degree of deformability, this thickness must be reduced and vice versa).

This technique makes it possible to reuse wet chalk while minimizing the quantities of treatment product. It does not, however, exclude the traditional technique using in-place mixing with ploughs, especially when it is difficult to produce the matrix with a horizontal shaft pulveriser (presence of flint, for example).

**Choice of treatment in the cut or on the fill**

**The benefit of treating in the cut** is to take advantage of the manipulations that are made on the soil during the successive phases of loading, unloading, spreading, etc., to improve the homogeneity of the soil-lime mixture and to produce maximum drying in evaporation weather conditions. This also improves the trafficability of the machines in the cut.

Another interest is to limit, if necessary, the diffusion of the dust of the treatment product by confining the treatment site to the inside of the cuts.

**The benefit of carrying out the treatment on the fill** is to be able to minimize the quantities of material to be treated. Indeed, by operating at the final stage of implementation, it is possible to select the areas really requiring treatment based on observation of soil behaviour (ruts of more than 10 to 15 cm under the wheels of transport equipment) or on measurements (bearing capacity at the plate or dynaplate, IPI or soil moisture content).

The choice of treatment method can then be based on the following considerations:

- if, based on the results of the surveys, it appears that the state of the soil requires treatment of almost the entire mass of excavated material, so it is preferable to provide for treatment "in the cut",
- if, on the contrary, it is found that a relatively large proportion of the soil located in certain poorly localised parts of the excavation during the survey is likely to be reused without treatment, it may prove more advantageous to treat locally "as much as necessary" on the fill, depending on observation of the behaviour of the material when it is laid.

## 7.3. OTHER SOIL TREATMENT APPLICATIONS IN EMBANKMENT CONSTRUCTION

### 7.3.1. General considerations on materials and techniques of execution

Since each application requires that the moisture state of the mixes be respected rigorously enough to guarantee the desired level of mechanical performance, it will be necessary to provide watering means whenever the moisture state of the natural material is "dry" or even "medium".

In addition, special arrangements may be required, as set out below.

### 7.3.2. Parts of specific works

***Filling of hard-to-reach areas***

The constraints of realization lie primarily in the duration of the supply of materials. All the manufacturing operations of the treated materials and processing must be carried out within the time limit of workability of the mixture.

In order to ensure the quality of mixing of the treated material, it must be manufactured:

- either by in-place treatment of excavated or borrow material, using high-performance pulverisers;
- either at the mixing plant and then transported to the place of implementation.

Compaction should, as far as possible, follow the recommendations in force for heavy and medium equipment when it can be used and for small compactors in the most confined areas (recommendations similar to trench backfilling).

***Technical embankments adjacent to engineering or hydraulic structures***

The materials and techniques of execution depend, if necessary, on the conditions of narrowness or steep slopes (see 5.2.2).

***Creation of the bases of high embankments with water-sensitive or rocky materials that can change with time***

For this application, all the materials and execution techniques developed for the reuse of excessively wet soils are applicable.

*Motorway A89 France / Pelites (Reference RT 2012 AIPCR)*

*RD 1089 – North by-pass of Brive / Pelites (Reference RT 2012 AIPCR)*
*Picture 40: Treatment of evolutive rock materials*

***Stiffening of embankment slopes***

As mentioned above for areas of difficult access, the treated material must be manufactured:

- either by in-place treatment using pulvimixers;
- either at the mixing plant and then transported to the place of implementation.

Padfoot compactors are well suited to obtain a better interlocking of the elementary layers.

<u>Possible realization techniques</u>

- When the definitive slope of the embankment must be acquired immediately, it is necessary to build a temporary support to ensure the stability of the embankment while waiting for the development of the hydraulic or pozzolanic setting.
- When this requirement is not imposed, it is possible to build the structure with a slope that guarantees its stability with the characteristics of the material "before setting" and to reshape the slope at an age when setting will have given it sufficient characteristics to ensure its stability at its final slope.

### 7.3.3. Improvement of the top section of earthwork (TSE)

For in-situ mixing, the general rule is the use of large horizontal shaft pulvimixers whenever the characteristics of the material (Dmax in particular) allow their use without excessive damage for the equipment. If this is not the case, ploughs may be considered, but an increase in the number of passes in the order of 50% over what is usual for treatment for reuse as fill in soils that are too wet should be anticipated.

Furthermore, as the thickness of the treated material is recommended to be at least 0.30 m, mixing with disc ploughs for TSE in cut will require the application of two layers with appropriate earth movement.

In principle, the compaction methods remain the same as those for a backfill core.

*Motorway A28*
*Placement of the treated capping layer in silts pre-treated with lime on stock*
*Picture 41: TSE and capping layer treatment worksites*

## 7.4. CONTROL ACTIONS

They include, in particular:

- verifying that the nature and state of the soils are consistent with the study assumptions,
- checking compliance with the requirements relating to the methods of execution: mixture manufacturing technique, accuracy of spreaders, types and characteristics of compactors, etc.,

Also according to the elements of the contract:

- either the verification of the conformity of the nature of the treatment product used and the quantities applied.
- either verification of the performance obtained with the treatment product and the dosage defined in the formulation study.

# 8. CARRYING OUT CAPPING LAYERS IN TREATED SOILS

## 8.1. GENERAL ORGANIZATION OF THE CONSTRUCTION SITES

### 8.1.1. Treatment equipment for mixing

In order to obtain the mixing and grinding qualities of the treated material for capping layers, mainly horizontal shaft pulvimixers with a power adapted to the nature of the material are used (see § 4).

For very large sites, the treatment plant may also be suitable after economic study.

### 8.1.2. Treatment Techniques / Elementary Operations

The production of capping layers made of soils treated with lime and/or hydraulic binders requires the execution of various elementary operations which must be carried out in a precise sequence. The phasing of certain tasks must take into account the workability period allowed for the mixture.

Figure 14 (GTS reference) shows the various elementary operations that can be involved in the execution of a treated capping layer.

Only a part of these elementary operations is to be carried out in all cases of construction site, they are:

- the production of the mixture (in place or in plant),
- the pregrading,
- the partial compaction,
- the final grading
- the final compaction,
- the application of the surface protection.

Others are to be carried out only if the nature and the state of the treated material require them, in particular:

- initial soil preparation
- surface closure,
- adjustment of the moisture state of the mixture,
- chipping.

There are several treatment techniques to consider:

1 / Supply at the location of the capping layer of a soil previously treated in plant or in place

2 / Supply of untreated soil at the location of the capping layer and in-place treatment with a hydraulic binder or lime alone

3 / Ditto 2nd case but the soil is subjected to a mixed treatment of lime + hydraulic binder.

4 / Treatment of a cut bottom (not requiring earth movements)

Refer to cases 2 or 3 depending on whether it is a treatment with a single treatment product or a double treatment, excluding the first 4 operations.

Figure 15 (Reference GTS France) shows operation scheduling for the four test cases.

This chapter develops the equipment and execution techniques specific to each of the elementary operations that are important for the quality of the work.

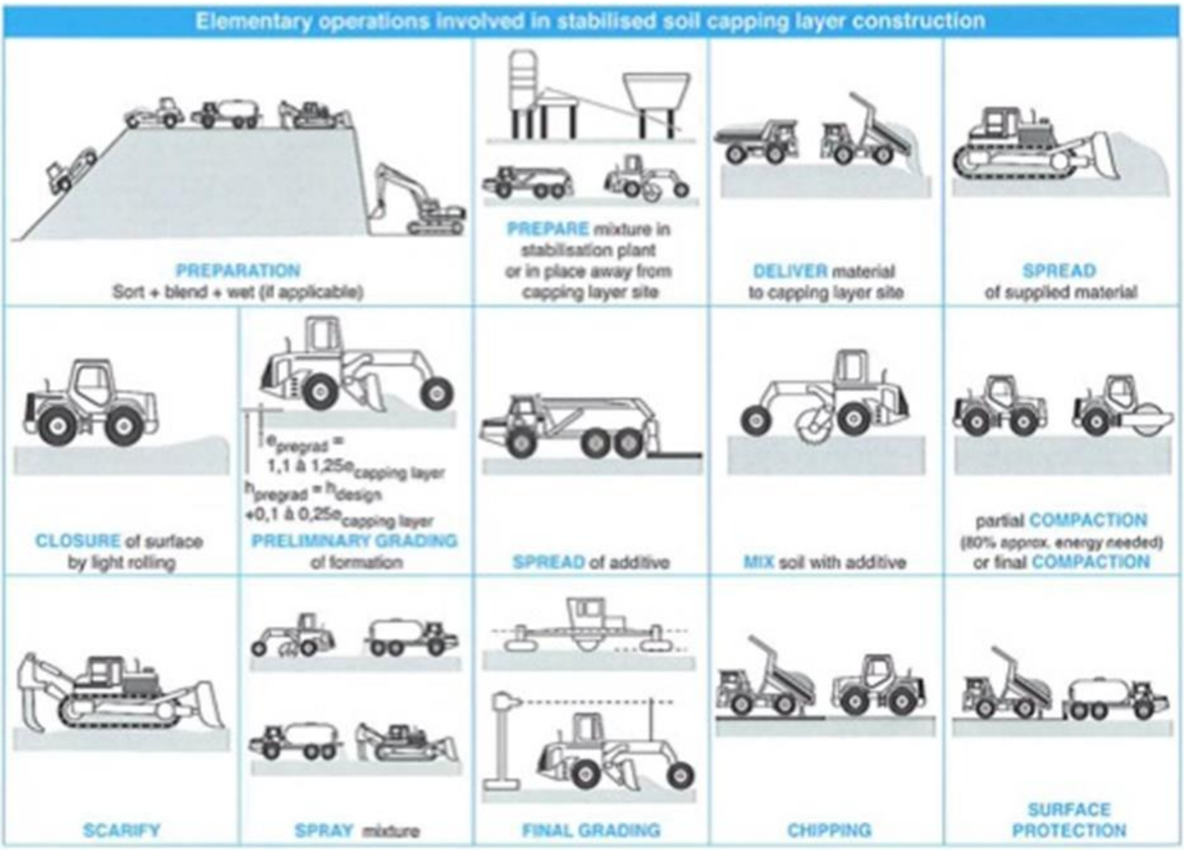



*Figure 14: Elementary operations for a treated capping layer*

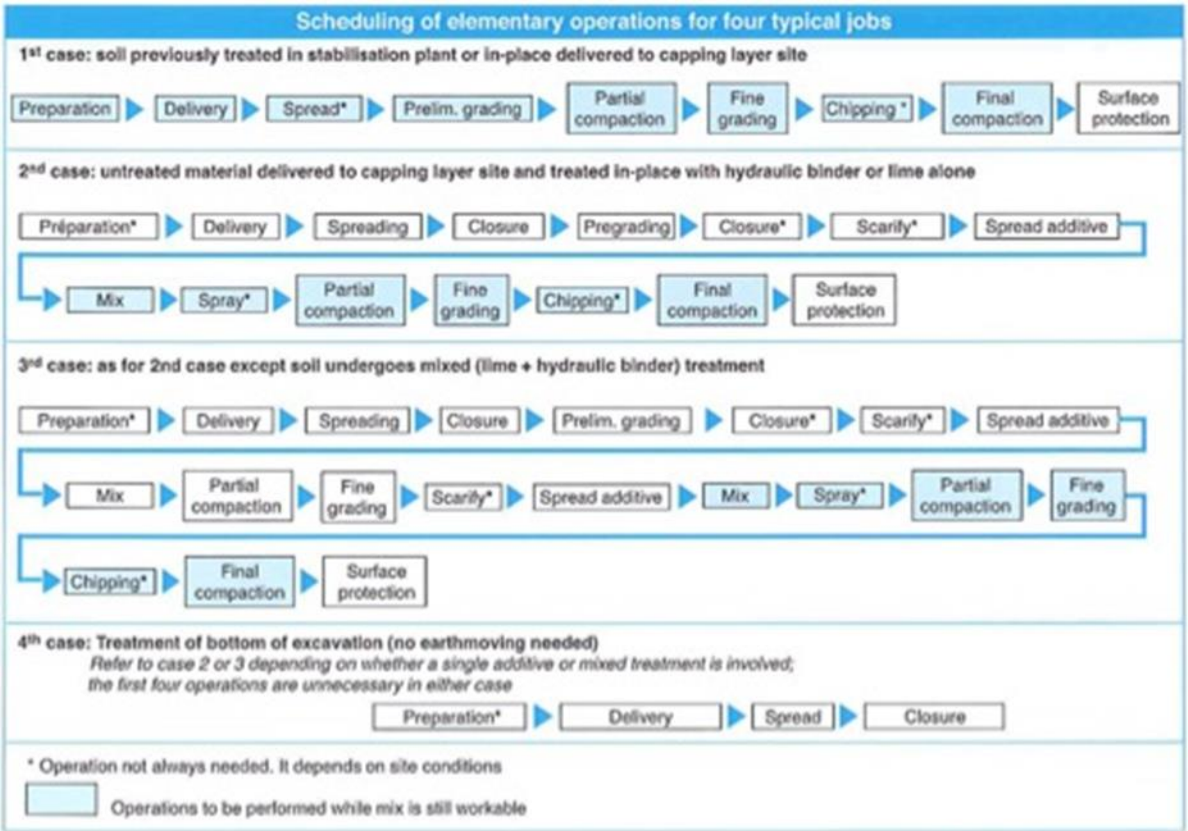



*Figure 15: Scheduling elementary operations for a treated capping layer*

## 8.2. PERFORMING BASIC OPERATIONS

### 8.2.1. Soil preparation

This operation includes all or part of the following actions:

- decohesion of the material in place by scarification,
- elimination of the coarse fraction preventing mixing,
- homogenization of the fraction suitable for mixing,
- humidification or aeration to change the moisture state of this same fraction.

***The decohesion of the material in place***

It can impose itself as already mentioned to:

- increase the productivity of the mixers,
- expand the material before moistening to allow better water penetration or, before spreading, to reduce dust emissions,
- bring up the big elements to the surface.

The material is mainly removed using multi-tooth rippers (usually three or more teeth spaced 40 to 60 cm apart) mounted on bulldozers or high-powered graders.

<u>Special case of chalk and soft rocks</u>

For this type of material, scarifying may not be appropriate to obtain the quality of the mixture, as it reduces the quantity of fine elements produced during mixing. It is indeed on the fine fraction that the treatment product is fixed to form the mortar aggregator of the coarse elements.

***The elimination of the coarse fraction***

The use of pulverizing equipment imposes limits on the size of the coarse fraction, generally **Dmax < 100 mm** (sometimes 150 mm depending on the petrographic nature of the blocks and the power of the pulvimixer).

In the case of the manufacture of the mixture in the plant, this value is reduced to 50 mm.

The coarse fraction can be removed by several methods:

- by grouping and collection using specific, mainly agricultural, machinery,
- by grouping and collecting with specific, mainly agricultural, machinery after the blocks have been brought to the surface by scarification,
- by screening
- also by crushing in place using a specific stone breaking machine (Photo reference DOURGES).

## GTR and GTS References / Various processes

### (1) Use of mobile screens

Many materials require the removal of their coarse fraction in order to be usable as a subgrade. To do this, several techniques can be considered, in particular the use of mobile screens such as the one shown in the Illustrations below.

Laoding a screen.

Ejection of coarse elements by tilting the grid actuated by the loader bucket during its reverse gear.

### (2) Loading through a grating attached to the dumper bucket

Loading trucks trhough a coarse screen fixed aver the back is a good technical solution but debatable in cost terms.

Screen on truck.

Loading trhough screen.

Removing blocks from glacial till (class C1B5m) with a mobile screen operated by the loading machine has proved to be an attractive solution on large jobs.

Screen and oversize blocks dumped aside.

Laoding a truck.

**(3) Homogenisation by means of provisional stockpiling**

Example of stockpiling glacial till (class C1B5m) at sereval points along route. Material screened and rebandled for in place treatment with hydraulic binder.

Same exemple with silt pretreated with quicklime

*Picture 42: Construction sites Capping layer / Coarse fraction removal*

For small sites, it may be possible to proceed manually, after the blocks have been brought to the surface by scarification.

Note

This operation is all the more difficult to carry out as the material has a large and humid clay matrix. Lime pre-treatment using an "embankment" technique can, in certain cases (CiBjh class soils in particular), considerably facilitate the separation of big elements by screening.

***Homogenization of materials***

When the investigation of the deposit has revealed the heterogeneity of the materials, the operating method that allows to correct it must be determined.

The homogenization techniques used are mainly the following.

Homogenization during extraction and loading

This is the most commonly used method when you can see the layers, pockets, lenses, etc. to be sorted in the deposit.

Separation is carried out either with scrapers or by stacking the materials (in heaps or in cordons), then taking them back with shovels or loaders.

The separated materials are then subject to separate earth movements.

Homogenisation during extraction and loading followed by temporary storage and recovery

This method is the most reliable, but it has a higher cost which must be assessed in relation to the level of quality provided. This level is to be sought in particular in the case of taking into account the capping layer in the design of the pavement.

The interest of a deposit-recovery can, moreover, be justified according to the soils and the constraints of organization of the construction site:

- by earth moving (e.g. where it is planned to set aside fine surface soils to create the capping layer)
- by the method of production (in particular plant processing).
- to either moisten the material as described below,
- or to its pre-treatment with lime, if applicable (in this case, the impact of the storage time on the behaviour of the soil pre-treated with lime during its recovery must be assessed).

***Moistening***

Objective

The purpose of this operation is to obtain, if necessary, a change in the moisture state of the material to be treated. It must be distinguished from the sprinkling operation, which only aims at a final adjustment of the moisture state of the mixture at the final stage of its implementation.

In general, a water content value close to the middle of the range defining the "h" state of the natural soil should be aimed for at the end of moistening, due to the immediate actions of the treatment products and the evaporation during production and processing.

Method

In order to ensure a homogeneous distribution of water in the soil, moistening should be carried out on the scarified material over about two thirds of the layer thickness taken into account in calculating the quantities of water to be spread. These quantities must not exceed values corresponding to an increase in water content of 2 to 3 % per sequence. Several sequences may be necessary to achieve the desired objective.

In view of the quantities of water required and the difficulties in achieving its homogeneous incorporation, this operation is no longer realistic in practice as soon as the water requirement exceeds 5 to 7 %.

Adapted equipment

The water supply must be controlled quantitatively (for example, it is desirable to equip sprinklers with pumps that are controlled by the speed of the vehicle and with flow meters for monitoring purposes).

In addition, the spilled water should not concentrate or run off in the tracks of the vehicle, hence the use of remote spray booms, for example.

The use of underground sprinklers allows the material to be deeply moistened.


*Motorway A89: Capping layer in treated silts (photo RAZEL)*
*Humidification with burying sprinckler*
*Picture 43: Capping layer Job site with humidification*

### 8.2.2. Spreading of treatment products

Techniques for the production of capping layers in treated soils

- the technique of spreading "by bag" on pre-grided platforms to delimit the area corresponding to the mass of a bag is technically acceptable. It is virtually inapplicable for obvious operational and economic reasons, with the exception of small construction sites or complex geometry.
- where a double treatment is provided for, the lime may be applied in accordance with the accepted treatment methods for the reuse of excessively moist soil as fill
- In other cases the permissible spreaders are at least volumetric metering spreaders, the spread rate of which is governed by the forward speed of the spreader. Their flow rate range should, as far as possible, be sufficient to spread the desired total mass in a single pass.
- Spreading must be carried out over the entire area to be treated in parallel strips adjacent to each other edge to edge or better with an overlap of a few centimetres to compensate for the width of the slope of each strip (in order to compensate for spreading irregularities, not only longitudinal but also transverse).
- The spreading accuracy must be checked according to the methods described in § 4.4 of the present booklet.
- Suitable spreading equipment.

Compliance with the mixing conditions is greatly facilitated by the use of modern spreaders including:

- a dosing unit with a single-pass flow rate of 50 kilograms per square metre,
- A device for checking and recording (possibly discontinuously) the spread mass per unit area (e.g. weigh cell mounted tank and distance measurement by special sensors),
- the possibility of varying the spreading width,
- Driving aids and in particular a warning signal when the tank is about to be emptied and at the same time the spreading process is automatically stopped.
- various devices to limit dust emissions from treatement products.

The use of binders, quicklime or HRB, including additives such as oil or other products, limits the volatilization of dust.

### 8.2.3. Mixing in place

With the exception of the special cases described in § "Aspects related to particularities of the building site" below, in-situ mixing of the soil with the treatment product(s) must be carried out with horizontal shaft pulvimixers. These machines produce a mixture of a quality comparable to that obtained in a manufacturing plant, as long as uniformity of spreading in both the longitudinal and transverse profile is achieved. However, unlike power plants, these materials are able to properly mix clay and wet soils.

Mixing with these machines must also be carried out in parallel strips, but with an overlap of at least 5 to 10 centimetres.

The general descriptive elements concerning these materials have been presented in § 4.5 of the present booklet.

With regard to their use for the realisation of capping layers, the important points to consider are the following.

***The value and regularity of the thickness of the mixed layer***

This is a decisive factor, particularly when the capping layer is included in the calculation of the pavement structure. In this case, the thickness mixed must be controlled within the tolerances taken into account in the design of the structure.

With regard to the regularity of thickness, machines whose mixing chamber is suspended between two axles offer a much better guarantee than those derived from agricultural equipment where the chamber is carried at the rear of the tractor.

***The fineness of grinding***

Grinding means the dimensional distribution of the mortar clods in the soil (fraction less than or equal to 0.4 mm) mixed with the treatment product which is observed at the exit of the pulvimixer.

Milling depends, all other things being equal: on the soil to be treated, the type of pulvimixer and its modalities of use as specified below.

Pulvimixers with the rotor rotating in the opposite direction to the drive wheels produce the finest grind.

The more clayey and humid the materials are (Reference France: Soils of classes A2h and especially A3h), the coarser the grinding will be. With these materials, a pre-treatment with quicklime should most often be carried out, with the mixing being carried out in at least two sequences, at least 4 hours apart, with, if necessary, a surface closure by light compaction in between.

***The maximum block size***

Almost all current horizontal shaft soil pulvimixers are equipped with spades (or picks) with tungsten carbide tips that can be used on soils with 50 mm stony elements without significant damage. With some newer, more powerful machines, this dimension can go up to 100 mm or even 150 mm.

***The possibility of injecting water directly into the mixing tank***

This possibility is especially interesting for precise adjustment of the moisture state of the mixture, but is generally not suitable for humidification requiring more than two points of water content.

### References GTR and GTS

When moisture content adjustment needs adding no more than one or two per cent water, a good solution consists of introducing the water directly into the pulveriser mixing chamber if it is equipped in consequence (pump delivery interlocked with forworad speed with tanker not shown on the photograph moving alongside).

*Picture 44: Capping layer Job site / Device for injecting water into the mixing chamber*

***The presence of anti-dust devices***

Mixing with modern soil pulvimixers does not constitute a major source of dust emission of treatment products, provided that the water conditions required for the proper processing of the mixture are met.

Note, however, that devices may include the possibility of injecting water directly into the mixing vessel.

***Aspects related to particularities of the building site***

Narrow construction sites

In the case of worksites that do not allow the correct evolution of large pulvimixers (widening of roadways, small worksites with complex geometry, etc.), more manoeuvrable equipment, such as rotary spades, may be suitable (subject to a demonstration on a test board).

Stony soils

In the case of double treatment of stony soils, the mixing of the soil during pre-treatment with lime can be carried out using ploughs. After pre-treatment, coarse material can often be screened out, allowing a large pulvimixer to be used to mix the soil with the hydraulic binder.

### 8.2.4. In-Plant production

Interest of plant production

Experience has shown that the production of soils treated with lime or hydraulic binders in plants equipped in particular with data acquisition modules for continuous production could offer a better guarantee of quality than in-place production, provided that the mixes flow correctly into the various organs (hoppers, dosing units, mixers) of the plants.

This can be explained by the greater control of dosages, and above all of the moisture state of the mixtures, and also by the need to build up stocks for the power stations, which significantly improve the homogeneity of the soils to be treated.

*RN 33 France Treatment plant with hydraulic binders / Sand and fly ash mixtures (Photo GTM Terrassement)*

*Picture 45: Construction sites capping layers treated in central mixing plant*


(1)

(2)

*Motorway A837 France Hydraulic binder treatment plant / Crushed soft limestone 0/60 mm*
*(Photos GTM Terrassement)*
*Picture 45bis: Construction sites capping layers treated in central mixing plant*

Mixture production in the plant

The quality of flow in mixing plants is a major constraint, sometimes difficult to resolve. The quality can be considered satisfactory with non-coherent soils (or slightly coherent soils that have undergone pre-treatment with lime followed by storage for at least a few days).

As stated above, the generally accepted limits for soil passage in conventional mixing plants are:

$$D_{max} \leq 50 \text{ mm and } I_p \leq 12 \text{ (or } VB_S \leq 1{,}5 \text{ g)}$$

**Reference GTR / soil classes B2, B4, B5**

These values are indicative. They can be significantly outdated:

- by carrying out various mechanical modifications to the power plants
- above all, by carrying out a pre-treatment with lime prior to processing in the plant

When the soils to be treated contain more than 5% fines, we recommend weight dosing plants.

Taking into account the constraints induced by these aspects and the costs involved, particularly transport costs, production in a mixing plant is reserved for sites with a large volume of materials to be processed (indicatively more than 50,000 m$^3$).

### 8.2.5. Compaction

The quality of a treated capping layer is closely related to its compaction. In particular, its fatigue strength varies greatly with the level of densification obtained at the lower part of the layer called "bottom of the layer" dry density (ρdfc).

The methods of using compactors to achieve the required densification objective for all capping layers must be defined.

**Reference France (GTR) See in Appendix 5**

Compaction quality " q3"

This objective is expressed by:

"bottom of the layer" dry density

$$\rho_{dfc} \geq 96 \text{ \%} \ \rho_{dOPN}$$

“average" dry density

$$\rho_{dm} \geq 98{,}5 \text{ \%} \ \rho_{dOPN}$$

However, in the case of capping layers in soils treated with lime and/or hydraulic binders, specific additional provisions described below shall, where appropriate, be added to the requirements set out in the tables of the GTR.

***Provisions relating to compliance with the "q3" density target***

**- a. Need for powerful compactors**

As the thickness of a treated capping layer is usually 0.35 m (sometimes 0.40 m), compaction in a single elementary layer of such thickness to reach the "q3" level requires powerful compaction means. Without these means, the application of the capping layer must be done in at least two elementary layers. In this case and unless there are exceptions (final compaction of each layer carried out within a period far less than the workability period, guarantee of absence of lamination at the layer interfaces, etc.), the Interface shall, with regard to the mechanical functioning of the structure, be considered as of the "sliding" type.

**- b. Need for rapid compaction in two phases: main compaction and final compaction of closure**

**Main compaction**

Partial compaction is carried out, depending on the job site, either after pregrading, if the material is supplied already treated, or after completion of the mix design, if the soil is treated in place and not transported.

Partial compaction should provide about 80% of the energy required to achieve "q3" quality.

The aim of partial compaction is to obtain, immediately after spreading, a density that is already quite high (around 95% of the final compactness) and homogeneous over the entire thickness of the layer. Once completed, partial compaction should be immediately followed by final grading.

**Final compaction (closing)**

Final compaction must be carried out immediately after final grading. Its purpose is to provide the additional compaction energy required to obtain the "q3" quality and, if necessary, to redensify the upper part of the layer that has been disorganised by the planing resulting from the final grading.

It is recommended to use for this compaction phase, a heavy pneumatic tyred roller. It should be used for this second phase because of its better ability to avoid the phenomenon of lamination.

In any case, compaction (partial compaction and final compaction) must be completed before expiry of the workability period of the mixture (and even significantly earlier if chipping of the platform is planned (see picture 46).

***Arrangements related to the lamination of the upper part of the capping layer***

Compaction very frequently generates a network of roughly horizontal cracks in the upper part of the layer (2 to 5 cm deep, or even deeper depending on the soil and the workshop). In the case of treated soils, this phenomenon, known as "lamination", often has an unfavourable effect that is often significant, because the cement bonds are not able to recreate, after setting, a mechanical continuity of the material throughout the entire thickness of the layer.

The use of vibratory padfoot rollers and the adjustment of the moisture state to near the "wet" value are modalities that significantly reduce the risk of lamination.

Indeed, experience shows that the factors favourable to the development of lamination through compaction are:

- the granulometric uniformity of the treated soils, especially when their D50 is in the 50/200 µm range, and all the more so as their moisture state is close to the "dry" state (this mainly concerns fine sands of the "dune sands" type, sands of classes B2 and B5 as well as fine soils with little plasticity A1),
- the use of heavy smooth-running vibrating cylinders (classes V4 and V5).

The method currently recommended consists, during fine adjustment, of eliminating most of the laminated area produced by partial compaction and then carrying out final compaction with 35t P2 class pneumatic tyred rollers.

*Construction site capping layer in treated fly ash LE HAVRE*
*Recommended compaction with tyred roller / Checking the density with a gammadensimeter*
*Picture 46: Job site Capping layer / Final compaction heavy pneumatic tyred rollre*
*(Photo GTM Terrassements)*

***Other compaction provisions that may apply***

Intermediate compaction may be necessary on some construction sites.

Additional compaction means may be required to solve specific problems such as lamination, pregrading, surface sealing, etc.

***Realization of systematic trial area***

In most cases, one or more trial areas should be made to specify the compaction conditions.

These cases may concern the nature of the materials, the action of the equipment or the search for superior performance.

### 8.2.6. Moisture status adjustment

The purpose of this operation is to adjust the moisture state of the mixture in such a way that it is within the tolerances envisaged in the study at the final stage of the treatment operations.

**If the soil is too wet before treatment**, solutions to correct this situation are fairly simple, either by aeration (using the pulvimixer) or by a quicklime treatment (or by increasing the quicklime dosage in the case of a double treatment).

**If at the end of mixing the material is too dry**, which is often the case, the effect of this condition on the difficulty of meeting the requirements of compactness is decisive. These conditions mean that watering is almost always necessary, even when the soil was in a moist water state prior to treatment.

The increase in water content referred to in this operation must remain limited, generally to 1 to 2 %. The watering must be started after the penultimate pass of the mixer using the equipment described for humidification.

The adjustment of the moisture state must be carried out on a bulk soil with equipment that controls the quantity and distribution of the water spread.

Suitable equipment

- Spraying via **remote sprayer booms**, supplied by a tractor speed related variable rate pump, between the penultimate and the last pass of the pulvimixer.
- For an addition of more than 1 to 2% water, a good solution is to introduce the **water directly into the mixing chamber of the pulvimixer**, if it is equipped accordingly (variable flow rate pump controlled by the forward speed and supplied with water by a tank moving in parallel.

### 8.2.7. Grading

***Purpose and specificity of this operation***

The purpose of this operation is to produce a layer of treated material whose final thickness is in accordance with the value considered in the design of the pavement structure, taking into account the permitted grading tolerances.

In the case of capping layers in treated soils, it is not acceptable to carry out the final adjustment by clipping the "over-profiles" and transferring the clipped material into the "under-profiles" and then re-compaction, due to the certain risks of destructuring the treated material.

It is absolutely recommended to carry out the final adjustment by planing off a certain oversize - as small as possible - over the entire surface of the capping layer.

***Organisation of the work site induced by the imperatives of the adjustment***

In order to carry out the final adjustment correctly, the following basic operations must be carried out: adjustment, pregrading, partial compaction, final grading (see Figures 47 and 48). These shall be completed no later than three-quarters of the mixing time to allow sufficient time for final compaction and, in the case of fine soils, chipping.

**a. The spreading**

This operation is to be considered mainly in the case of the supply of a previously treated material.

**b. The pregrading**

This operation is to be carried out whatever the case of building site. Its purpose is to create a platform with such a dimension that, after feeding, possible adjustment, spreading, mixing, possible watering, partial compaction, there remains, at any point on the surface of the capping layer, an excess thickness which will be removed during the final grading operation.

**c. The final grading**

The purpose of this operation is to remove and evacuate the excess thickness left on the entire surface of the layer after partial compaction.

The levelling tolerances to be searched for are generally ± 3 cm, but for large construction sites, especially motorways, the search for a value of ± 2 cm (or even ± 1 cm with fine soils) is realistic considering the adjustment workshops generally used (autogrades, wire- or laser-guided graders or especially GPS).

***Grading workshops***

They may consist of:

- conventional graders guided manually by means of boning rod,
- motor graders guided electronically by wire and proximity sensor or by laser plane, GPS
- specific machines such as wire or laser-plane guided autogrades which can simultaneously perform regaling/distribution, pregrading, cording and pick-up/loading of excess material.

Pregrading is usually done with a grader, more and more often laser guided. Final grading is a key phase in the implementation of the capping layers, during which the precise leveling is carried out and, if necessary, the laminated part is removed. It works with a grader for small jobsites, with a planer or autograde on larger ones. Here again, contactless guidance has become widespread.

*(1) Grading capping layer with a grader (Photo CIMBETON)*

*(2) Grading with a grader (Photo DTP Terrassement)*
*Picture 47: Job site Capping layer / Grading workshop*

*(1) (1) Grading of the capping layer with Rotograde 2000*
*(Photo GTM Terrassement)*


*(2) Rotograde RABAUD/GTM (Photo GTM Terrassement)*
*Picture 48: Construction site Capping layer / Grading Rotograde*

The choice of the workshop depends on the importance of the construction site and the topographical constraints of the project. As an indication, workshop outputs are shown in the table below.

| Type of structure | Plant generally appropriate | Indicative daily productivity (8 hrs work) |
|---|---|---|
| Standard motorway or railway | Grader + laser or wire guidance system or if possible wire guided autograder | 8000 to 12,000 m² |
| Airfield runway | Grader + laser or wire guidance system or if possible wire guided autograder | 6000 to 10,000 m² |
| Wide radius bend motorway or railway | Wire guided grader or if possible wire guided autograder | 4000 to 10,000 m² |
| Industrial platform | Grader + laser system | 2500 to 5000 m² |
| Taxiway | Grader + laser system or wire guidance | 2000 to 4000 m² |
| Small and moderately-sized road. Slip road | Grader + pegs or if possible wire guided grader | 1000 to 2000 m² |
| Narrow road, work on contraflow section | Grader + pegs | 500 to 2000 m² |
| Carriageway junctions | Grader + pegs | 500 to 1000 m² |

*Table 16: Choice and indicative output of final grading workshops according to the type of structure*

### 8.2.8. Chipping

Chipping is recommended on capping layers platforms (fondation level) made of fine treated soils to withstand intense traffic. Its role is to allow the adhesion of heavy surface protection (single or even double-surface dressing) which will necessarily have to be carried out to support this traffic.

Chipping is also very advantageous on these materials to improve the bond between the capping layer and the treated sub-base (with hydraulic as well as hydrocarbon binder).

This operation generally consists of spreading and embedding on the platform, after final grading and final compaction, gravel with a Los Angeles coefficient of 35 or less, crushed, 3/8 mm or 10/14 mm or large gravel such as 14/20 mm or more, at a rate of 5 to 7 kilograms per square metre (as an indication).

The embedding must be carried out before the end of the workability period by two to three passes of a smooth cylinder operating without vibrating, of class V1 at least, or better using a class P2 pneumatic tyred roller.

**Note**: Chipping differs from the surface protection techniques developed below, on the one hand, because it must be carried out within the workability period, so that the "nails" can be sufficiently embedded before setting and retained in the material after setting and, on the other hand, because it cannot claim to have any effectiveness in controlling the hydrous state of the mixture during its setting.

### 8.2.9. Surface protection

A surface protection of the capping layers in treated soils is necessary.

The type of protection depends on the objectives sought, the nature of the materials treated, and the mechanical and climatic stresses supported.

***Objectives of surface protection***

The surface protection must in any case:

- maintain the moisture state of the treated material constituting the capping layer (protection against both infiltration and evaporation), during the period of hydraulic setting of the treated soil,
- promote bonding between the capping layer and the sub-base layer.

Most of the time the capping layer is designed to withstand construction site traffic.

The surface protection must then ensure:

- a significant increase in the resistance of the platform to the tangential forces transmitted by the tyres as well as a reduction in slippage in the event of rain (role similar to that of chipping),
- a reduction in dust emissions from transport equipment.

***Different types of surface protection***

The main types of surface protection are generally those described in Table 17. Most of them come from the surface dressing technique.

#### Reference jobsite LE HAVRE (treated fly ashs)

**Various steps**

Surface closure by pneumatic tyred roller and topographic reception

Nailingl with a 10/14 aggregate

Emulsion dosed at 800 g/m2 for effective coverage, then chipping with a 4/6 aggregate

*Picture 49: Job site Capping layer / Surface protection*

| Name - Sketch | Formulation (per m²) | Remarks |
|---|---|---|
| Sprayed water (P) | 1 to 2 litres of water, possibly with hydrophilic product (CaCl2) | Water must be sprayed in finely divided form. Renew operation when surface becomes dry and dust begins to form. |
| Sprayed emulsion curing agent (EC) | 0.5 to 0.8 kg emulsion* + clean sand or small gravel to refusal** | Sand can be used only if there is no heavy traffic on capping layer. (cf table C2-VII) |
| Seal coat (ES) | 0.8 to 1.1 kg emulsion* + clean sand or small gravel to refusal** | Similar protection as (EC) but more effective against drying if exposed for a long time (cf table C2-VI). |
| Single surface dressing (EM) | 1.3 to 1.6 kg emulsion* + 7 to 8 litres 4/6 gravel** or 9 to 10 litres 6/10 gravel** | Choice of gravel depends on aggressiveness of traffic. Emulsion rate can be increased to 5% to 10% depending on surface roughness. |
| Double surface dressing (EB) | 1st layer<br>1.1 to 1.3 kg emulsion*<br>10 to 11 litres 10/14 gravel**<br>2nd layer<br>1.5 kg emulsion<br>6 to 7 litres 4/6 gravel** | Quantity of emulsion in the first layer to be adjusted with reference to surface roughness. |
| Prechipped surface dressing (EP) | 8 to 9 litres 10/14 gravel** + 2 kg emulsion + 6 to 7 litres 4/6 gravel** | This protection is comparable to what is afforded by single surface dressing on a chipped formation. |

* Weight per unit area for 65% bitumen cationic emulsion
** Gravel must have a Los Angeles coefficient < 35 and cleanness (% < 0.08mm) < 2%

*Table 17: Surface protection systems applicable to stabilized soil capping layers (Reference GTS)*

***Solicitations to consider***

Between the end of its laying and its covering by the sub-base layer, a capping layer is subjected to different types, durations and intensities of stress, depending on the construction site.

The most important are traffic and climate and the length of exposure it will have to endure during this period.

**Reference:** GTR France

**See Appendix 7:** Compaction requirements

## 9. CARRYING OUT TREATMENTS / CONTROLS

Controls concerning the treatment of embankment bodies, special embankments, TSE and capping layers are specified in the technical parts of the contracts. They must intervene before, during and after the treatment of the materials.

## 9.1. PRE-TREATMENT CONTROL

The controls are first of all based on the imperative need to know the nature and the moisture state of the material, in order to determine its classification and the dosage of binder that will be necessary.

Another important point of these controls is to check the compliance of the lime when it is used in the processing operation, including its reactivity.

## 9.2. CONTROLS DURING TREATMENT

During processing, it is necessary to carry out controls to ensure that the following parameters are mastered:

- the coefficient of variation $C_v$ of the spreading of the binder, in particular by means of the tarpaulin test, which is expressed by the relation:

$$C_v = \frac{s}{\overline{m}} \times 100$$

With **s** standard deviation on mass measurements / m$^2$ and **m** average of measurements

- the amount of water to be added to the material;
- the thickness of the material to be treated;
- the homogeneity of the grind (mixing and soil-water-binder mixture).

## 9.3. CONTROLS AFTER TREATMENT

Most of the monitoring is focused on the parameters below:

- measurement of the water content with a view to a possible correction (by additional mixing) of the quantity of water to be incorporated;
- precautionary sampling of binder samples for possible verification of conformity;
- possible taking of samples for the measurement of the immediate load-bearing index (IPI);
- checking after compaction:
  - densification, usually measured with a gammadensimeter, a membrane densitometer or a sand cone,
  - bearing capacity in the short term, by measuring the modulus under static loading at the EV2 plate or by measuring the dynamic modulus at the dynaplate, and in the long term by measuring the deflection.
- mechanical characteristics by means of coring to determine the couple ($R_t$, E).

### 9.4. Trial and reference areas

As a general rule, trial and reference areas are carried out on the construction sites in order to define and validate the implementation criteria of the treated materials.

## 10. REFERENCES TECHNIQUES

### 10.1. General references

See the Manual Preamble

Notably:

Standard EN 16907: Earthworks

- Part 1: General principles and rules;
- Part 2: Classification of materials;
- Part 3: Construction processes;
- Part 4: Treatment with lime and / or hydraulic binders;
- Part 5: Quality control;
- Part 6: Dredged hydraulic backfill;

Technical guide (France)
Technical guide (GTR) - Realization of backfill and subgrade (Setra - LCPC; 2nd edition July 2000)

- Booklet 1: General principles
- Booklet 2: Technical Appendices

### 10.2. Specific elements Treatments

European standards

EN 16907-4: Earthworks - Treatment with lime and / or hydraulic binders

EN 197-1: Cement - Composition, specifications and conformity criteria of common cements

EN 459-1: Building lime - Definitions, specifications and conformity criteria

EN 13282-1: Liants hydrauliques routiers - Liants hydrauliques routiers à durcissement rapide — Composition, spécifications et critères de conformité

EN 13282-2: Hydraulic road binders - Normal hardening hydraulic road binders - Composition, specifications and conformity criteria

European technical guides

Germany: Supplementary Technical Contract Provisions and Guidelines for Earthworks in road construction (ZTV E-StB 09) – (FGEV; 2009)

Belgium: Recommendations - Code of good practice for the treatment of soils with lime and / or hydraulic binders (CRR; 2009)

Spain: Manual de estabilización de suelos con cemento o cal (Ancade – Anter – Ieca)

France: Technical guide (GTS) - Soil treatment with lime and / or hydraulic binders; Application to the production of backfill and subgrade (LCPC – Setra; 2000)

United Kingdom: Definitive Industry Guidance - Soil Improvement and Soil Stabilisation (Britpave; 2017)

Sweden: Terrasstabilisering Kunskapsdokument (VTI rapport 747; 2012)

### 10.3. BIBLIOGRAPHICAL SOURCES

The bibliographic sources (articles, presentations, etc.) used for the drafting of the Manual are in particular the following:

International seminars “Earthworks in Europe”

1 / Paris, October 2005

2 / Londres June 2009

3 / Berlin March 2012

4 / Madrid June 2018

International congresses

Tremti 2005 – Paris, France, October the 24-26th 2005

Tremti 2009 – Antigua, Guatemala, November the 11-13th 2009

France seminar

Terdouest 2013 (Soil treatment for sustainable earthworks) – Marne la Vallée, June the 18-19th 2013

Publications

Dallas N Little: Handbook for stabilization of pavement subgrades and base courses with lime (Lime Association of Texas; 1995)

## 11. TERMINOLOGIE / GLOSSAIRE

### 11.1. GENERAL ELEMENTS

See the Manual Preamble

Notably:

Standrads reference EN 16907-1: Earthworks - Principles and general rules)

## Definitions

***Capping layer***

*Specific transition layer, located in the upper zone of the earthworks, placed under the superstructure. The capping layer is an integral part of the earthwork*

***Classification***

*Defining classes and assigning materials to classes with similar properties for earthwork*

***Compaction***

*Densification of the embankment's material by a mechanical process in order to obtain the prescribed properties for the embankment*

***Compactness or degree of compaction (of the backfill)***

*Ratio of the in-place dry density of the compacted embankment's material to the maximum dry density, obtained by means of a standard compaction test performed in the laboratory*

***Compaction effort***

*Overall measure of the force applied to compact a layer of embankment, reflecting: the mass of the compactor / m2, the number of passes, the speed of the roller, the frequency of vibration and the thickness of the layer*

***Embankment***

*General term used in this standard to describe all earthen structures formed by the placement of an embankment's material in a controlled manner for technical purposes (in particular, infrastructure's embankment, backfill's embankment, platforms, etc.)*

***Embankment area***

*Subdivision of an embankment into several parts, including the base, core, shoulders and top*

***Embankment structure***

*Earthwork carried out by embankment (associated with linear infrastructures or platforms)*

***Excavation***

*Linear earthwork formed by an excavation process*

***Materials***

*Soils, rocks, industrial by-products and recycled mineral materials used during earthworks for the construction of earthworks.*

***Trafficability***

*Capacity of the surface of a material to withstand the passage of earthmoving machinery*

***Treated material (of embankment)***

*Material (embankment) modified by adding a binder*

***Superstructure***

*Civil engineering structure installed on the earthen structure (example of superstructures: roadway, railway track, buildings, gantries, etc.)*

***Unsuitable material***

*Embankment's material unsuitable for use in its current state because its properties before compaction do not meet the requirements of the technical specifications for earthworks. These materials can become suitable after treatment to adjust soil properties*

***Water content***

*Ratio of the weight of water contained in a particular sample to the weight of dry soil*

## 11.2. Specific elements Treatments

Standard reference EN 16907-4: Earthworks - Treatment with lime and / or hydraulic binders

### Definitions

***Aerial lime***

*Lime that hardens by combining with carbon dioxide in the air*

***Binder***

*Product or combination of products which, when mixed with a material, brings about a short-term or long-term change in the properties of the material*

***Cement***

*Hydraulic binder, that is, a non-organic material reduced to a fine powder which, when mixed with water, forms a paste which sets and hardens under the effect of reactions and hydration processes and which , after hardening, retains its strength and stability even under water*

***Cure period***

*Period of time during which a treated mixture is stored after final compaction, under prescribed conditions to limit evaporation and allow the stabilization process to continue*

***Fly ash***

*Fine powder produced by the combustion of pulverized coal or lignite, with or without co-combustion material, in power generation plants and captured by mechanical or electrostatic filters*
*Fly ash can be:*

- *siliceous, when the essential chemical components are silicates, aluminates and iron oxides;*
- *calcium, when the essential chemical components are silicates, aluminates, oxides of calcium and sulphates.*

*Siliceous fly ash is a pozzolanic material that needs a source of calcium oxide, such as lime or cement, to produce a hydraulic reaction.*

***Hydraulic binder***

*Binder which, when mixed with water, hardens in air and under water and which remains solid even under water*

***Hydraulic road binder***

*Hydraulic binder produced in the factory, delivered ready to use, whose properties are specifically adapted to the treatment of materials for base layers, foundation layers and sub-layers, as well as for earthworks, in infrastructures road, rail, airport or other type*

***Lime***

*Calcium oxide and / or hydroxide and calcium-magnesium oxide and / or hydroxide produced by thermal decomposition (calcination) of naturally occurring calcium carbonate (eg, limestone, chalk, shells) or calcium carbonate - naturally occurring magnesium (e.g. dolomitic limestone, dolomite)*
*Air lime is lime that can be in the form of quicklime, hydrated lime or milk of lime.*

***Whitewash***

*Suspension of hydrated lime in water, produced from quicklime or hydrated lime, in a specific device, in a lime production plant or on site*

***Maturation period***

*Period during which a mixture of cohesive material and lime is left to stand after light compaction, if necessary, in order to promote migration of lime into the clumps of material created during mixing and to aid the improvement process*

***Pozzolanic material***

*Material that does not harden on its own when mixed with water, but reacts at normal room temperature with dissolved calcium to form cementitious compounds capable of developing strength*

***Slag***

*In this document, means granulated blast furnace slag*

***Soil improvement***

*Operation which changes the physical properties of a material in the short term - for example, water content, plasticity, compaction ability and swelling potential - by adding a binder.*
*The amount of binder added may not be sufficient to induce lasting properties.*

***Soil stabilization***

*Operation which consists in obtaining a homogeneous mixture of soil with one or more binders and possibly water, which, after suitable compaction, significantly increases (generally in the medium or long term) the characteristics of the soil so as to make it stable, especially against the action of water and freezing*
*Stabilizing a soil gives it lasting characteristics that can be measured by methods typical of solid materials.*

***Soil treatment***

*General term to indicate a process whose objective is to modify a soil, so that the mixture resulting from the addition of one or more binders to this soil can fulfill the intended objective*
*The term "treatment" includes improvement and stabilization.*

***Workability delay***

*Time calculated from the end of mixing, during which the binding of the binder is zero or very low and during which all the implementation operations must be completed, including compaction and adjustment if performed with a grader*

## 12. BIBLIOGRAPHICAL REFERENCES

Refer to the references cited in the text and the Appendices

# TECHNICAL APPENDICES

# TABLE OF CONTENTS

# APPENDIX 1

## PIARC REFERENCE 2007R09

## TECHNICAL REPORT " PROMOTING OPTIMAL USE OF LOCAL MATERIALS "

## Extracts concerning the treatment of materials

### [1.4 TECHNIQUES AND METHODS]

Some progress has been made with regard to the following types of applications:

- treatment of dry or very dry soil with lime slurry. This technique, used frequently in the United States for several years now, was recently intro¬duced in some Southern European countries;
- two-step treatment of sulphite soils. The treatment for this type of soil is preceded by a step in which the initial formation of ettringite is ensured by adding lime and moisturing;
- more frequent treatment of recycled materials, trench cuttings or excess earthwork materials;
- development of soil treatment for pavement bases instead of using high-quality granulated materials.

Stabilizing the formation level (consisting of the upper part of the embankment, the bottom of the excavation, and more generally, the subgrade) is becoming more widely-used technique on highway construction sites and on roads with heavy traffic.

Studying the behaviour of the treated materials, as was discussed during the international forums, allows us to determine the resulting durability from using the treatment, but also the difficulty in controlling the delicate period during the setting time, which often coincides with or closely follows the spreading and compaction activities of the treated material.

It can be observed that a wide range of natural materials such as soils or rocks have been the subject of treatment studies with, however, a strong predominance for fine silty or medium clayey soils. However, strongly clayey materials appear in some applications as well as products resulting from the alteration of granitic or lateritic rocks.

The geotechnical characterization of materials is always carried out with conventional tests as the Proctor and CBR tests, Atterberg limits, methylene blue value, particle size analysis, etc. The most widely recognized mechanical perform¬ance test for treated materials is the unconfined compression test, sometimes complemented by the triaxial tests, direct box shear apparatus tests or diametral compression or tensile tests. In some cases, the modulus of resilience is also measured. Tests specific to treated soils have sometimes been developed, such as the French treatment suitability test, which aims to detect the presence of setting disturbing elements in the material to be treated.

Particular emphasis has been put on the influence of sulphates in soil treatment using lime or Portland cement. Some developments have been made with respect to methods of testing sulphatic soil and the construction techniques used to prevent swelling.

The recent bibliography also indicates an interest in technologies aimed at stabi¬lizing organic soil, which is difficult to treat with cement or lime because of the interference of organic matter in the binder setting process. Some other consid¬erations come into play in cases where there are, for example, large amounts of mica minerals in the soil.

Durability is a key factor when studying the behaviour of treated soil, especially with respect to climate.

In terms of key research areas, there appears to be a growing interest in attempting to better understand the macroscopic behaviour of treated soil through the physical and chemical processes that occur at the microscopic level. Analytical and inves¬tigative tools such as X-ray diffraction, thermogravimetry, electron microscopy or even MRI are without a doubt contributory factors in advancing our under¬standing of these processes.

## [1.5 REFERENCE MATERIAL]

In recent years, major legislation and technical reference documentation (such as technical manuals, test methods, standards and directives) have been developed mainly in Western European countries and the United States. As previously noted in PIARC's 2005 study, it appears that legislation is a necessary factor for soil development. This factor is a trigger in that it encourages the use of specialized techniques and without this legislation the techniques cannot be implemented. Legislation is thus a contributory factor in the technique development. As a result, there is a correlation between the development of soil treatment techniques and the production of relevant legislative documentation.

Below is a list of some reference documents on soil treatment such as technical documents and standards. For the most part these documents, drafted in recent years, come from European countries. This list is not exhaustive and cites only some of the references from PIARC's 2005 study.

- Germany: Manual on soil stabilization and soil improvement with binders (FGSV N° 551);
- Austria: Technical contract conditions: superstructure, road base, stabi¬lization of road bases with binder (RVS 8S 05 13); Technical contract conditions: base course, stabilization with lime (RVS 11 245);
- Belgium: Code de bonne pratique pour le traitement des sols à la chaux et/ou au ciment,

  Recommandations de Centre de Recherches Routières (CRR R74/04); Guide pratique d'Amélioration des sols pour le remblayage des tranchées d'égouts et l'enrobage des tuyaux (CRR 74/04); Guide pratique de stabilisation des sols pour couches de sous-fondation (CRR 74/04); Guide pratique d'amélioration des sols pour terrassements et fond de coffre (CRR 74/04);

- France: Guide technique du traitement à la chaux et/ou aux liants hydrauliques, application à la réalisation des remblais et des couches de forme (LCPC-SETRA); Soil treatment with lime and/or cementitious binders, application to the construction of fills and capping layers; Guide technique de traitement des sols à la chaux et/ou aux liants hydrauliques, application à la réalisation des assises de chaussées;
- Italy: Stabilizzazione delle terre con calce (Bolletino CNR 36/1973); Tratta¬mento delle terre con calce (RFI): Trattamento delle terre con cemento (RFI);
- Slovakia: Road Building. Stabilized Bases (STN 736125).

# APPENDIX 2

## USA REFERENCE

## Article from « National Lime Association » October 2006

## Mixture design and Testing Procedures for Lime Stabilized Soil

## Technical Brief:

### Mixture design and Testing Procedures for Lime Stabilized Soil

The use of lime to dry, modify, and stabilize soil is a well established construction technique, documented in studies dating back to the 1950s and 1960s [see Ref. 1]. A variety of mixture proportioning procedures have evolved, as various agencies have developed criteria and procedures to fit their specific design needs and objectives, often reflecting local conditions and experience [1].*

The procedures outlined in this publication are intended for soil that is to be stabilized with lime, not merely dried or modified. These procedures are intended to help ensure the long term strength and durability of a lime stabilized soil and are not typically required when soil drying and modification is the desired goal. Other laboratory tests, such as measuring decrease in soil moisture content or reduction in plasticity index (PI), are more appropriate when soil drying/modification is the intended result.

In 1999, the National Lime Association commissioned Dr. Dallas Little to evaluate various procedures and develop a definitive lime stabilization mixture design and testing procedure (MDTP) that specifying agencies, design engineers, and laboratory personnel could use with confidence for soil conditions and environmental exposures throughout the United States. The resulting series of reports summarize the literature on lime stabilization [2, 3]; describe mix proportioning and testing procedures for lime stabilized soil [4]; and present a field validation of the protocol [5].

### Lime-Treated Soil – Drying, Modification, and Stabilization

Lime has a number of effects when added into soil [6, 7], which can be generally categorized as soil drying, soil modification, and soil stabilization:

Soil drying is a rapid decrease in soil moisture content due to the chemical reaction between water and quicklime and the addition of dry material into a moist soil. [8]

Modification effects include: reduction in soil plasticity, increase in optimum moisture content, decrease in maximum dry density, improved compactability, reduction of the soil's capacity to swell and shrink, and improved strength and stability after compaction. These effects generally take place within a short time period after the lime is introduced – typically 1 to 48 hours – and are more pronounced in soils with sizable clay content, but may or may not be permanent.

Note: the modification action corresponds to the improvement action according to PIARC terminology.

Lime stabilization occurs in soils containing a suitable amount of clay and the proper mineralogy to produce long-term strength; and permanent reduction in shrinking, swelling, and soil plasticity with adequate durability to resist the detrimental effects of cyclic freezing and thawing and prolonged soaking. Lime stabilization occurs over a longer time period of “curing.” The effects of lime stabilization are typically measured after 28 days or longer, but can be accelerated by increasing the soil temperature during the curing period. A soil that is lime stabilized also experiences the effects of soil drying and modification.

### Steps for Mixture Design and Testing for Lime Stabilized Soil

- Evaluate soil to gain a general understanding of its suitability for lime stabilization.
- Determine minimum amount of lime required for stabilization.
- Evaluate lime-stabilized soil strength for long term durability within its exposure environment, with special attention to cyclic freezing and thawing and periods of extended soaking.

If soils to be stabilized are expansive, evaluate using capillary soaking and expansion measurements.

# APPENDIX 3

## EUROPEAN STANDARD REFERENCE

## Extracts from Standard EN 16907-4 Earthworks - Part 4: Soil treatment with lime and/or hydraulic binders

## Feasibility of the stabilization treatment of materials and taking into account disturbing or harmful components of the soil to be treated.

### [7.3 Feasibility of treatment]

Feasibility of treatment depends on grading and of the nature of the components of the material.

a) Grading (including the maximum particle size as indicator) shall be compatible with the performance of the equipment (mixer, roller, grader, etc.) as well as with the geometric requirements, particularly regarding the thickness of the layers after compaction.

For stabilization, depending on the hardness of the particles, the maximum particle size should be less than 150 mm, unless the equipment is capable of easily achieving the specified parameters with larger particles.

The final particle size of the mixture shall be in accordance with the rules for compaction.

NOTE 1 For options on methods to remove particles which are oversize, refer to 9.6.3, Particle size correction.

b) It should not contain any constituent in a proportion which would adversely affect the performance and volumetric stability of the treated material.

The assessment of the risk due to the presence of deleterious elements is indicated in Clause 8 of this standard.

NOTE 2 Organic matter can reduce or prevent the setting and hardening process. Laboratory mixture design work will determine whether soil containing organic matter can be accommodated. The amount of organic matter that can be accommodated depends on the type of organic matter.

NOTE 3 Soil containing or suspected of containing sulfur, sulfide or sulfate can result in expansion of the mixture. Laboratory mixture design work including ‘resistance to water testing’ in accordance with this European Standard will determine if material with the potential to cause swelling can be accommodated. Limiting values of swelling due to the presence of sulfide and sulfate are defined through the swelling measured according to 8.2.5 of the Standard. Limits to the proportion of these deleterious materials may also be set in national practices.

NOTE 4 The informative Annex G gives examples of field and laboratory identification procedures of common sulfide and sulfate minerals.

### [9.1.2 Prerequisites]

The purpose of these prerequisites is to ensure that the possibility of treatment of materials using binders is considered from the outset.

Before starting earthworks operations a preliminary study should be carried out in accordance with Clause 7 and subclause 9.2 of the Standard to check and update data included in the design of the earthworks. For that purpose, further site investigation and ground investigation may be carried out.

For soil improvement special emphasis shall be given in confirming the water content and checking for the presence of deleterious materials. For soil stabilization the focus is confirmation of the material type, the available quantities and distribution, and again checking for the presence of deleterious materials.

NOTE The suitability of materials expected on site for treatment may be noted on the drawings. This will allow an initial and very broad assessment to be made of the quantities of materials likely to be available for stabilization.

### [9.2.3 Sulfide, sulfate, organic matter and other deleterious materials]

Neither the soil, nor the groundwater, shall contain proportions of potentially disruptive or deleterious components that, after binder addition, result in poor performance and/or excess swelling of the mixture.

The assessment of the risk due to the presence of deleterious elements is indicated in Clause 8 of this standard.

Limiting values of swelling due to the presence of sulfide and sulfate are defined through the swelling measured according to 8.2.5 of the Standard.

NOTE 1 The informative Annex G gives references for field and laboratory identifications of common sulfide and sulfate minerals. The informative Annex K gives a checklist of tasks to be undertaken, particularly with respect to the deleterious elements.

NOTE 2 Limits to the proportion of these deleterious materials may also be set in national practices.

### [8.2.5 Swelling]

When required, the swelling of the mixture shall be examined using either linear swelling or volumetric swelling described in 8.3.3.3 and 8.3.3.4 of the Standard.

NOTE These tests are measuring the total swelling due to the presence of remaining expansive clay as well as the presence of deleterious products like sulphate.

### [8.3.3.3 Linear swelling after soaking in water]

When required, the linear swelling, determined on at least 3 fully soaked (immersed) CBR specimens in accordance with EN 13286-47, using water that is continuously aerated, shall conform to the selected category from Table 12. The soaking shall follow a conditioning period. The swelling shall be examined for at least 28 days or until swelling ceases if longer. The specimens shall be manufactured from the same batch of mixture.

NOTE The conditioning period will usually be the same as that selected for the determination of CBR index in 8.3.2 of the Standard.

Table 12 — Linear swelling ($L_S$)

| Average maximum linear swelling ($L_S$) of the specimens | Maximum linear swelling ($L_S$) of any individual specimen | Category |
|---|---|---|
| 5 mm | 10 mm | $LS_5$ |
| 1 mm | 2 mm | $LS_1$ |
| 2 % | 4 % | $LS_{2\,\%}$ |
| Declared value | Declared value | $LS_{DV}$ |

### [8.3.3.4 Volumetric swelling after immersion in water]

When required, the volumetric swelling Gv shall not exceed 5 % when tested in accordance with EN 13286-49.

NOTE Where the volumetric swelling is greater than 5 % but does not exceed 10 %, the use of the mixture is generally not possible; however, a complementary study can be made according to experience at the place of use.

# APPENDIX 4

## EUROPEAN STANDARD REFERENCE

## Extract from Standard EN 16907-4 Earthworks - Part 4: Soil treatment with lime and/or hydraulic binders

## Field and laboratory identifications of common sulfide and sulfate minerals

## [**Appendix G** (informative)]

### [G.1 Field Identification]

#### G.1.1 Pyrite (FeS2 – Iron Sulfide)

Pyrite is the most common sulfide mineral which has a very distinctive brassy yellow colour with a metallic lustre in reflected light It can be recognized when present in large amounts. Pyrite is common as cube shaped crystals and the faces of the crystals are striated. It also occurs as irregular grains and masses. It is particularly common in shales, slates, mudstones and heavily over-consolidated clays.

If pyrite is present in particles too small for field identification, identification is possible only by binocular microscope or X-ray diffraction analysis.

#### G.1.2 Marcasite (FeS2 – Iron Sulfide)

FeS2 can also be present as marcasite which has similar characteristics to pyrite but has a different crystal structure, being more tabular in appearance. It is much less common than pyrite and is generally found as nodules in the coal layers. Marcasite is likely to be as troublesome as pyrite in engineering terms and should be treated with as much caution.

#### G.1.3 Gypsum (CaSO4.2H2O – Calcium Sulfate)

Gypsum crystals are generally white, grey or clear, although yellow, red and brown discolorations occur. The crystals of gypsum are columnar, tabular and needle-shaped in appearance ranging in size from coarse to fine grained. Gypsum occurs in evaporitic rocks and as the weathering product of sulfides in sedimentary rocks. It is particularly common in some overconsolidated clays, and occurs in clusters, some of them large, and in discontinuous sheets. Gypsum can be damaged by the finger nail and, when it is in a well developed crystal form, it is commonly referred to as selenite.

### [G.2 Laboratory Identification]

#### G.2.1 General

It is emphasized that the descriptions of the material from the core, or from or in the trial pit, are the key methods for locating the presence of sulfides and sulfates. The laboratory testing will give a precise figure for the sulfur content, both as sulfide and as sulfate, at a particular location but will not give an overall assessment of the distribution of sulfur minerals.

### G.2.2 Sulfide Minerals

Sulfide minerals do not have an expansive reaction with lime or hydraulic binder but have the potential to oxidize to sulfates which do. Also the oxidation process itself can cause expansion as the reaction produces sulfuric acid which reacts with any calcium or magnesium carbonate present and leads to the formation of gypsum (calcium sulfate) or epsomite (magnesium sulfate): both of these occupy a greater volume than the original chemical components. The calcium and magnesium carbonate can be present either within the sulfide bearing soil itself or placed adjacent to it. For example, both calcium and magnesium carbonate can occur in limestone. Sodium sulfate minerals which also have expansive properties are less common than calcium sulfate minerals and are highly soluble like magnesium sulfate.

### G.2.3 Sulfate Minerals

Ettringite (Ca6Al2(SO4)3(OH)12) is formed by the combination of soluble sulfates, from gypsum for example, and dissolved alumina, produced by the effect of the high pH associated with adding lime. The crystallization of ettringite is expansive and, in addition, is subject to further large volume changes as it takes in water. Thaumasite (Ca3Si(CO3)(SO4)(OH)6) will also form from ettringite but without a change in volume. Although ettringite and thaumasite occur naturally, they are not common and their expansive properties are only realized principally when the ettringite forms as a result of adding lime and water to sulfate bearing soils. Both ettringite and thaumasite are unlikely to be identified in the field during the ground investigation. Identification is only necessary after laboratory samples have been stabilized and swells observed, as this gives an indication of likely behaviour during stabilization.

Ettringite and thaumasite may be identified in the stabilized material as colourless and white needle crystals with a vitreous lustre.

## [G.3 References]

As the potential damage from soils containing sulfide and sulfate is considerable, reference should be made to national guides related to the treatment of soils.

# APPENDIX 5

## EUROPEAN STANDARD REFERENCE

## Extract from Standard EN 16907-4 Earthworks - Part 4: Soil treatment with lime and/or hydraulic binders: Appendix D (informative)

### Example of evaluation of performance variability of treated soil as a result of variation during implementation

### Binder percentage adjustment and method for compensating it

Evaluation of the effects of variation during implementation on the performance of the treated material and the possibility of compensating it by adjusting binder percentage may be studied from the diagram ($E-R_t$) shown in Figure D.1 and according to the procedure described below.

Figure D.1 shows the performance classification method as explained in 8.3.2.4.4 “Method by indirect tensile and compression testing” of the Standard. According to this diagram, Zone 1 corresponds to the higher level of performance, Zone 5 to the lower level of performance.

Points A, $A^+$ and $A^-$ represent the ($E-R_t$) couples measured for different predetermined binder percentages.

Points $A_1$, $A_2$ and $A_3$ represent the ($E-R_t$) couples obtained after predetermined modifications of the specimen characteristics as shown in the table of Figure D.1.

It is possible from this diagram to identify what are the preparation conditions that give the lowest performance. In this example, conditions represented by $A_1$ (0,9 d; 96% pdOPN; 1,1 $W_{OPN}$) gives the lowest performance

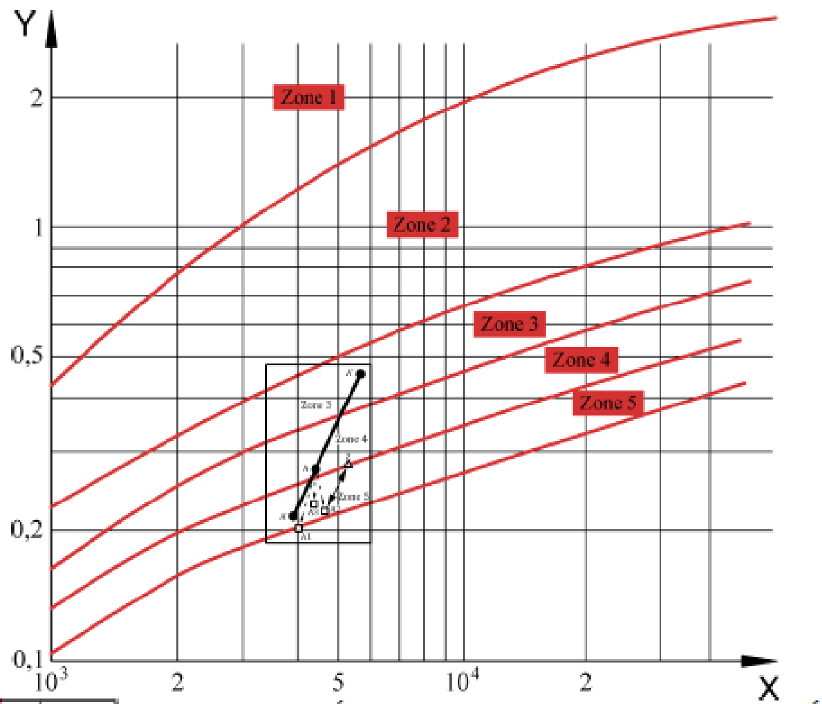
Thus, it is possible to compare the relative impact of the variation different factors on the final performance. It may lead to looking for tight control of the density of the treated material and/or its water content rather than compensating by an excess of binder percentage.

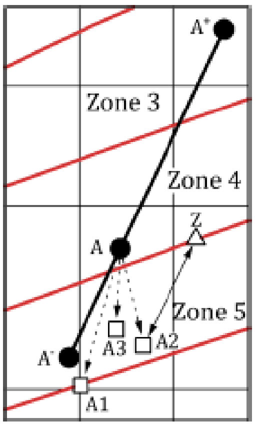
If compensation of performance reduction by an excess of binder percentage appears however the most appropriate, the excess binder percentage can be calculated as follows:

- It is accepted that the progression of the points representing the ($E-R_t$) couples is linear when the binder percentage varies from d- to d+ (as shown in Figure D.1 by the straight line $A^-$ $A^+$).
- On this assumption, if, starting from conditions represented by $A_2$, the binder percentage is increased from d to d+, it may be considered that the points representing the ($E-R_t$) couples move parallel to $A^-$ $A^+$ brought by $A_2$.
- To calculate the excess of binder percentage for compensating the unfavourable effects of construction variation, it is therefore advisable to draw through $A_2$ the parallel to $A^-$ $A^+$ which cuts the zone 4 boundary at point Z (which is the position assumed to be aimed at). The corrected binder percentage value de may then be calculated by a direct proportional relationship between segments length A2Z and $A^-$ $A_+$ according to the formula:

$$d_c = d + \left( \left( d^+ - d \right) \frac{A_2Z}{AA^+} \right)$$

Conversely if none of the points $A_1$, $A_2$ and $A_3$ is below the limit of the targeted zone where point A is positioned (which means that the additive percentage selected for the sensitivity survey was overvalued), the same approach may then be followed to calculate the additive percentage reduction which complies with the performance level sought.




MODES ACCEPTÉS DANS LA CONCEPTION DE LA SENSIBILITÉ

| Point | Pourcentage de liant | Masse volumique | Teneur en eau |
|---|---|---|---|
| $A^-$ | $d^-$ | 96 % $\rho_{dmaxOPN}$ | $w_{OPN}$ |
| $A^+$ | $d^+$ | 96 % $\rho_{dmaxOPN}$ | $w_{OPN}$ |
| A [a] | d | 96 % $\rho_{dmaxOPN}$ | $w_{OPN}$ |
| $A_1$ | 0,9 d | 96 % $\rho_{dmaxOPN}$ | 1,1 $w_{OPN}$ |
| $A_2$ | 0,9 d | 94 % $\rho_{dmaxOPN}$ | $w_{OPN}$ |
| $A_3$ | 0,9 d | 96 % $\rho_{dmaxOPN}$ | 0,9 $w_{OPN}$ |

[a] Le point A représente la performance du mélange de référence.

**Légende**

X = $E$ (MPa)

Y = $R_t$ (MPa)

**Figure D.1 — Méthode graphique pour calculer le pourcentage de liant supplémentaire exigé pour compenser les variations de mise en œuvre**

# APPENDIX 6

## GTS France REFERENCE

## Soil treatment in capping layers / Formulation studies
## Sizes and methods of making specimens

### [2.3. Formulation study to be performed on other types of jobsites]

On jobsites which cannot be classified as small as defined above, a formulation design study is necessary and is performed as follows.

### [2.3.1 Sizes and methods of making specimens]

Specimen size depends on the Dmax of the material and the type of strength test to be performed on it.

The soil is mixed with the additive(s) in the manner described in French Standard NF P 94-230-3 deleted and replaced by standard NF EN 13286-53 for soils with no or very low clay content (classes B1, B2, B3, B4 , D1, D2, etc) and NF P 98-093 or also NF EN 13286-2 for other soils (using the special mixer described in the informative annexe to this Standard,*cf.* § B-1.3.1.b.).

The strength tests used in formulation studies are taken from the following list [22]

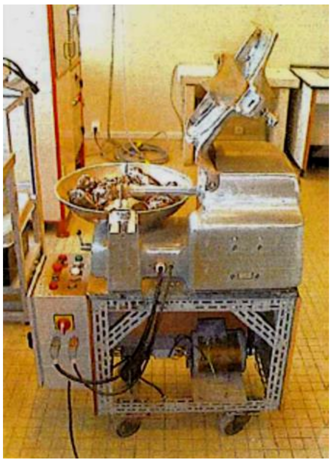
- concentrated shear strength tests (ICBR after 4 days immersion and IPI),
  - cf Standard NF P 94-078 or also NF EN 13286-47,
- uniaxial compression resistance test (Rc),
  - cf Standard NF P 98-232-1 deleted and replaced by NF EN 13286-41,
- Brazilian tests (Rtb),
  - cf Standard NF P 98-232-3 deleted and replaced by NF EN 13286-42,
- direct tensile strength test (Rt),
  - cf Standard NF P 98-232-2 deleted and replaced by NF EN 13286-40.

Special mixer for mixtures of coherent soils and lime and/or hydraulic binders [See Pictures (A) and (B)].

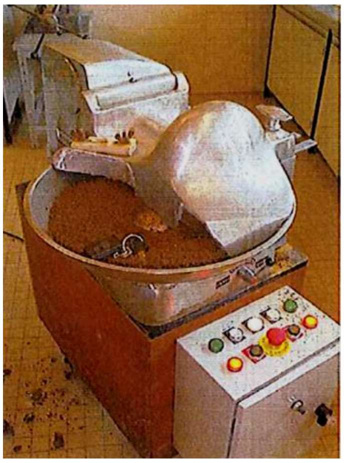
**(A) Mixer-disaggregator / Detail of mixer**

Note the bowl with soil clumps and powdered lime on top, top cover (open) and mixing blade on its shaft and underneath, the variable speed drive motor.

**Picture (A)**



**Picture (B)**



**(B) Mixer-disaggregator / Detail of mix obtained.**

After a few seconds mixing, the mixture appears as a tilth of perfectly homogeneous colour with a « grain size » of 0/5 millimeter.

### Processus

For the determination of the $I_{CBR}$ index (after four days immersion) and IPI index, the grading fraction tested, specimen size and method of making are described in Standard NF P 94-078 and NF P 94-093.

For the determination of $R_C$ , $R_{tb}$ and $R_t$ the fraction tested and minimum specimen diameter are shown in table below.

**TABLE C1-VI**

**Granular fractions and minimum specimen diameters for mechanical strength tests $R_c$, $R_t$, $R_{tb}$**

| Material | Granular fraction tested (mm) | Minimum specimen diameter (cm) |
|---|---|---|
| $A_1, B_1, B_2, D_1$ | 0/6 | 5 |
| $B_3, B_4, D_2, D_3$ | 0/20 | 10 |
| $B_5, B_6$<br>≥ 70% passing 2 mm<br>< 70% passing 2 mm | <br>0/6<br>0/20 | <br>5<br>10 |
| Ci $A_j$, Ci $B_j$ | 0/20 | 10 |
| Other materials | 0/6 if $D_{95}$ < 6mm<br>0/20 if $D_{95} \geq$ 6mm | 5 if $D_{95}$ < 6mm<br>10 if $D_{95} \geq$ 6mm |

The values shown are a compromise between the practicalities of the study and the possibility of transposing the results to field conditions. Compaction details (static or vibro-compression) are described in French Standards NF P 94-230-1 and NF P 94-230-2.

When the material exhibits a $20/D_{max}$ fraction, the study is performed on the 0/20mm fraction and in the absence of other sources of information (trial areas, past experience on similar jobs, etc.) the results are applied to the whole $0/D_{max}$ fraction **(1)**.

Slenderness ratio and densities are shown in table C1-VII. They refer to the type of test performed.

**TABLE C1-VIII**

**Specimen preparation versus test type**

| Test type | Slenderness ratio | Density | Compaction method |
|---|---|---|---|
| Uniaxial compressive strength (Rc) | 2 | 98,5% $\rho d_{OPN}$ | Vibro-compression or static compaction |
| Diametral compressive strength (Rtb) | 1 | 96% $\rho d_{OPN}$ | Vibro-compression ✱ or static compaction |
| Direct tensile strength (Rt) ✪ | Geometry specified in NF P 98-230-1 | 96% $\rho d_{OPN}$ | Vibro-compression |

✱ The method of compaction by vibro-compression for moulding specimens of slenderness ratio 1 is not explicitly considered in French Standard NF P 94-230-1 but it can still be used by modifying the apparatus described in that Standard (when moulding, insert two spacers of ad hoc dimensions on each piston)

✪ This test applies chiefly to soils whose D50 exceeds 2 mm (without excluding the Rtb test).

**(1)**

This simplification assumes that the $20/D_{max}$ and 0/20 fractions demand the same quatity of addictive (with reference to their respective masses), but this is necessarily incorrect in view of their different specific surface areas. It is nevertheless acceptable as a first approximation because it is conservative (because it leads toagreater abundance of additive for the 0/20 mm fraction, proportionally to the ratio between the specific surfaces of the total $0/D_{max}$ fraction and the 0/20 mm fraction). Research is in progress on a more objective assessment of the effects of this simplification.

# APPENDIX 7

## GTR France REFERENCE

## Compaction requirements

They are set according to the nature of the structures, in order to:

- limit the settlement of the fill bodies and ensure their stability,

- obtain sufficient stiffness and resistance characteristics for the capping layers.

Two densification objectives, symbolically designated by q3 and q4 (1) are defined:

- q3 objective usually required for capping layers,

- q4 objective usually required for embankments.

The prescriptions given in the compaction tables correspond to the definition of the modalities of use of the compactors for each couple: material - equipment.

(1) The densification targets q1 and q2, not considered here, apply to the pavement structure; q2 generally corresponds to a sub-base layer and q1 to a base layer. These objectives are defined in standard NFP 98 115

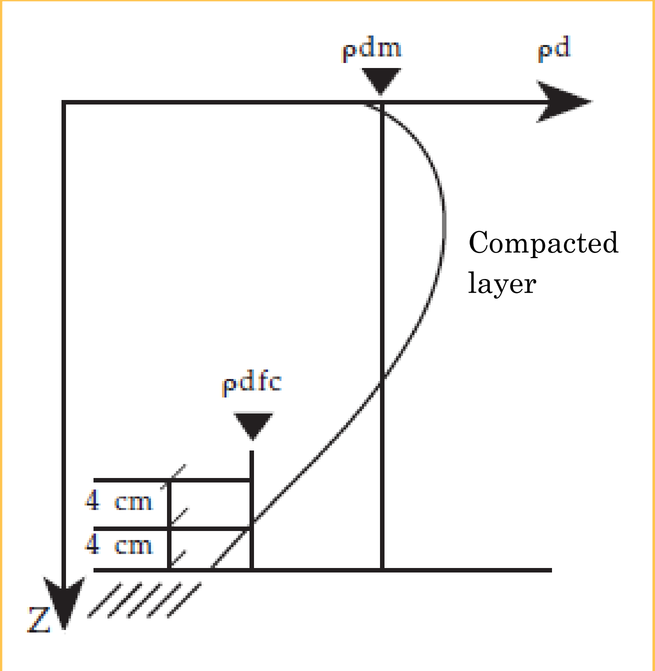
These prescriptions were set from numerous test sections accompanied by precise and repeated measurements of the density in place, the observation of the behavior of structures and a mathematical model calibrated on these data. This work of rationalization undertaken since the recommendation of 1976 led to revise some requirements following in particular repeated observations of marked insufficiencies of compaction at the bottom of the layer.

With the implementation by layer and the current equipment, we indeed observe a variation of the dry density on the height of the compacted layer, as illustrated in figure 7. To ensure a correct compaction, this leads to consider two indicators:

$\rho_{dm}$: average dry density over the entire thickness of the compacted layer.

$\rho_{dfc}$: dry density at the bottom of the layer; that is to say the average value over an 8 cm thick slice located at the bottom of the compacted layer.

Figure 7 Variation of the dry density over the height of the compacted layer.




The average prescriptions of the tables were established to reach the values,

q3 Densification objective for the compaction of capping layers:

$\rho_{dm} \geq 98.5\% \ \rho_d$ OPN and

$\rho_{dfc} \geq 96\% \ \rho_d$ OPN

q4 Densification objective for the compaction of embankments:

$\rho_{dm} \geq 95\% \ \rho_d$ OPN and

$\rho_{dfc} \geq 92\% \ \rho_d$ OPN

These values are to be considered as guides but should not be used as compaction requirements (non-relevance of the Proctor reference for many materials, factual impossibility of ensuring true and precise control of all works by measuring the density, particularly with regard to the base layer).

It will be noted that the density of the upper part of the layer is not directly taken into account here to characterize the quality of the compaction. Some specific provisions are however recommended depending on the material-equipment couple for this area.

When specific reasons lead to reconsider the prescriptions given in this document, it will be advisable to proceed to test sections to translate the prescriptions into modalities of use of the compacting equipment, like what is done in this document.

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