Study of the Potential of Raw Sediments and Sediments Treated with Lime or Cement for Use in a Foundation Layer and the Base Layer of a Roadway

Nor-Edine Abriak, Mahfoud Benzerzour, Mouhamadou Amar, Abdeljalil Zri

***Abstract*—**In this work, firstly we have studied the potential of raw sediments and sediments treated with lime or cement for use in a foundation layer and the base layer of a roadway. Secondly, we have examined mineral changes caused by the addition of lime or cement in order to explain the mechanical performance of stabilized sediments. After determining the amount of lime and cement required stabilizing the sediments, the compaction characteristics and Immediate Bearing Capacity (IBI) were studied using the Modified Proctor method. Then, the evolution of the three parameters, which are optimum water content, maximum dry density and IBI, were determined. Mechanical performances can be evaluated through resistance to compression, resistance under traction and the elasticity modulus. The resistances of the formulations treated with ROLAC®645 increase with the amount of ROLAC®645. Traction resistance and the elastic modulus were used to evaluate the potential of the formulations as road construction materials using the classification diagram. The results show that all the other formulations with ROLAC®645 can be used in subgrades and foundation layers for roads.

***Keywords*—**Sediment, lime, cement, roadway.

I. INTRODUCTION

A. GTR Classification of French Sediments

THE characterization of raw sediments according to the Technical Guide for Road Earthworks - embankments and subgrades (French acronym GTR) (LCPC-SETRA, 1992) [2] is a critical step for a subsequent study of hydraulic binders (Fig. 1). Table I summarizes the different types of characterization tests on raw sediments and the standards used for that purpose [1]-[4].

II. PHYSICAL CHARACTERIZATION OF SEDIMENTS

This section presents the physical characteristics of the materials used in this study as dredged sediments (F002). The objective is to identify sediment parameters like granulometry, organic matter content, density, loss on ignition and initial water content and to subsequently identify recovery solutions. The identification of raw sediments favors the proposal of a general methodology for recovery in road building using a binder.

TABLE I
DIFFERENT TYPES OF TEST ON RAW SEDIMENT

Type of characterization	Type of test	Standard
Physical	Water content by weight	NF P94-050 [26]
	Absolute density	NF P94-054 [31]
	Organic matter content (by calcination)	XP P94-047 [20]
	Granulometry (wet method)	XP P94-041 [32]
	Granulometry (by sedimentation)	NF P94-057 [27]
	Sediment blue value	NF P94-068 [28]
	Atterberg limit determination. Liquid limit test using cassagrande apparatus. Plastic limit test on rolled thread.	NF P94-051 [29]
	Atterberg limit determination. Liquid limit. Cone penetrometer method	NF P94-052-1 [30]
Mechanical	Proctor compaction Test (compaction characteristics)	NF P94-093 [6]
	IBI test (immediate bearing)	NF P94-078 [24]

TABLE II
INITIAL WATER CONTENT OF THE SEDIMENTS

	Drying oven at 40ºC	
No.	1	2
w (%)	14.8	*16.9*
average (%)	*15.9*	

A. Natural Water Content

Water content by weight, the most intuitive, provides a description of the moisture conditions in a material. In geotechnical studies, water content can be measured directly first of all by weighing the sample of material to determine a mass: m_h, then weighing it after evaporating the water completely in a drying oven to a constant mass: m_s. Water content (w%) is obtained according to:

$$w(\%) = \frac{m_h - m_s}{m_s} \times 100\% \quad (1)$$

According to Standard NF P94-050 (1995) [18], the material must be placed in a drying oven at 40 ºC. In this section, the water content of marine sediments was measured in a drying oven at 40ºC. The results are shown in Table II.

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B. Granulometry

Granulometric analysis aims to determine the weight distribution of the size of different families of grains in the studied materials. A grading curve enables quantitative evaluation of the different fractions of grain compositions: Clay, silt and sand (clay <2 µm < silt < 63 µm < sand). Several methods are currently used to analyze grain distribution in geotechnical materials, such as wet sieving (NF P 18-560) [19]. This method consists of fractioning a granular material through a decreasing series of sieve sizes. Mesh dimensions are chosen in relation to the aim of the test and the type of samples. The marine sediments were passed through 0.08 mm, 0.1 mm, 0.16 mm, 0.2mm, 0.25mm, 0.400 mm, 0.5 mm, 0.63 mm, 0.8 mm, 1.0 mm, 1.25 mm, 1. 6mm, 2.0 mm, 3.15 mm, 4 mm, 5 mm, 6.3 mm, 8 mm, 10 mm, 12.5 mm, 16 mm, 20 mm and 25 mm sieves. After pouring the dredged sediments onto the largest sieve, the sieves are shaken manually or mechanically or the materials washed through with water. After sieving, the waste is recovered and dried to obtain its dry weight.

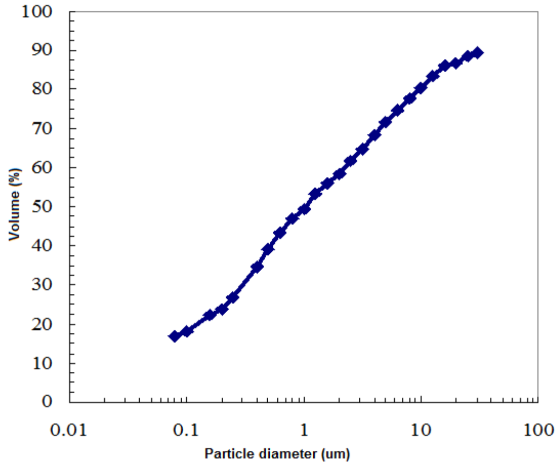

Fig. 1 Particle size distribution

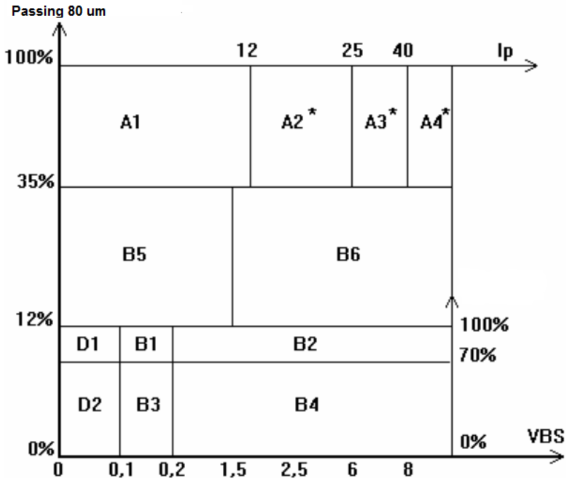

Fig. 2 Classification of the sediments [2], [21]

The particle size distribution in Fig. 1 confirms the fact that the dredged sediments contain a large proportion (83.1%) of grains larger than 80 µm. Dredged sediments can be very sandy sediments containing only 16.9% of grains smaller than 80 µm.

C. Absolute Density

Absolute density is a physical parameter that characterizes the mass of a material per unit volume. Absolute densities of solid particles in the materials studied were measured using a MICROMERITICS-ACCUPYC 1330 helium pycnometer.

The dried and ground sample is introduced in power form into a specific cell. After the cell is placed in the device, helium is injected to displace the air in the cell. According to the principle that PV = nRT, the acquisition system can record the pressure inside the system as a volume. The volume of the sample is the difference between the volume of the cell and the volume of injected helium. Therefore, absolute density can be calculated according to (2). For each test, 80 measurements were taken at different pressures and the mean was calculated. Three tests are required to verify sampling homogeneity.

$$\rho_{abs} = \frac{M_{measured}}{V_{measured}} \tag{2}$$

where ρ_{abs} is the absolute density (g/cm^3), $M_{measured}$ is the weighed mass of solids (g), $V_{measured}$ is the cell volume used (cm^3). In fact, the absolute density of the grains is essentially established by their mineralogical composition. The result is shown in Table II and the absolute density of the sediments is 2.67 g/cm^3.

D. Organic Matter Content

Organic matter has significant undesirable properties. It retains water and prevents pouzzolanic reaction, so organic matter content must be measured to take account of these phenomena. The impact of organic matter on sediment characteristics depends on the nature and structure of the organic matter [1]-[3]. Organic matter characteristics include a loose spongy structure with little mechanical strength.

TABLE III
ORGANIC MATTER CONTENT

Parameters	*F002*
450 °C (%)	*1.52*
550 °C (%)	*2.56*

According to standard XP P 94-047 (1998) [20], organic matter content determined by calcination is the ratio of the mass of organic matter to the dry mass of solid particles previously dried at 40 ºC that are less than 2 mm. The lost mass is calculated from the difference between the initial sample mass and its mass after calcination in an oven at 450 ºC for 3 hours. According to standard NF EN 12879 (2000) [5], loss on ignition can also be measured in an oven at 550 ºC for 3 hours. The results are shown in Table III. The interpretation of these results must be taken carefully because in addition to the loss of organic matter, the loss of sample mass is probably also associated with water loss, carbonate decomposition and a loss of certain mineral phases destroyed by the high temperature.

Fig. 3 Material for grinding and sieving dry sediments (from left to right: a 20 mm sieve, a knife and a roller)

Fig. 4 Grinding the sediments after oven drying

E. Classification of Sediments

According to the GTR (1992) [2] classification, marine sediments belong to the non-organic subclass, as the organic matter content is below 3% (1.52%). From the perspective of particle size, the proportion of fine particles under 80 µm is 16.9%. The subclass is determined in relation to the MBV. Thus, the studied sediments can be classified in the subclass B5.

III. COMPACTION AND MECHANICAL PERFORMANCE OF THE FORMULATIONS

A. Sample Preparation

1) Materials

- Dry sediments
- ROLAC® 645(for tests on treated sediments)
- Water
- Machines
- Mixer
- Drying oven
- Two scales
- Containers
- A roller for crushing the material

2) Experimental Protocol

First, sediments must be taken from the watertight barrels they were placed in after extraction. They are placed in boxes to put in the drying oven. After this stage, the boxes are removed from the oven so the dry material can be crushed and placed in bags after sieving to 20 mm (above that diameter, it is no longer considered sediment).

3) Making Samples with a Certain Water Content

The samples were produced by weighing the necessary amounts of water and dry sediments; for example, w=6% for m_8=6 kg, we used m_{eau}=360 g). Then they were mixed for 3 minutes. The mixer did not give a uniform mixture, so mixing was completed with the aid of a knife. Everything was placed in a bag that was closed hermetically.

4) Making Samples with a Certain Content of ROLAC® 645

Similarly, to obtain a certain content in ROLAC® 645, the desired quantity of material is weighed in relation to the dried sediment mass (for example, for m_S = 6kg and ROLAC 645 content is 8% and then we used m_{ROLAC}=480g. The materials are mixed for three minutes, and then left for ten minutes, and then left for ten minutes before use.

5) Determination of the Immediate Bearing Capacity of Untreated and Treated Sediments

a) Objective

The objective of the experiment is to determine the immediate bearing capacity of untreated and treated sediments with different water contents. This index characterizes the soil's capacity to support heavy machinery on its surface during works. It is therefore important to know the immediate bearing capacity if marine sediments are going to be used in subgrades. First, the test is carried out on untreated sediments. Then, we add 6% and 8% ROLAC® 645

6) Equipment and Materials

a) Equipment

- Two scales
- CBR mould with collars
- A screed
- Cups
- Machines
- Automatic Proctor-CBR compactor
- A press (IBI measurement)
- Drying oven

b) Materials

- Dry sediments
- ROLAC® 645(for tests on the treated sediments)
- Water

c) Experimental Protocol

The sample is compacted according to standard NF P 94-078 [24]. Previously, we prepared samples containing 6 kg of dry sediments and an amount of water corresponding to the desired water content. Here we have samples at 6, 8, 10 and 12%. Then, we performed the test using a modified tamper. The mould has to be filled five times. Finally, there will be five layers in total, each one compacted by 56 blows with the tamper.

After putting the third layer in place, we prepared two samples to determine the exact water content of the material. When the compaction process is completed, the top surface must be levelled with trowel to obtain a flat surface, particularly at the center of the sample.

Fig. 5 CBR mould with sediments ready to be compacted with the tamper

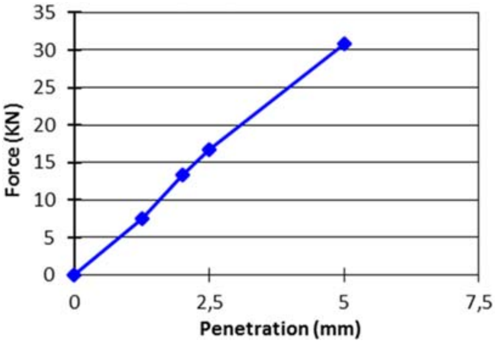

Fig. 6 Force-penetration curve for 8% water content and 8% ROLAC® 645

7) Measurement of Dry Density and Actual Water Content

a) Water Content

The actual water content in our sample was determined by filling 2 cups and measuring the wet weight.

The samples were taken from the drying oven after several hours to measure the dry weight. This procedure enabled us to deduce an average water content w, defined by:

$$\mathbf{w} = \frac{\mathbf{M_w}}{\mathbf{M_s}} * \mathbf{100\%} \tag{3}$$

b) Dry Density

To determine the dry density of a material, it is sufficient to weigh the mass of wet material after tearing the scale. Calculation of the mould volume gives the wet density. Thus, the following relationship gives the dry density of the material:

$$\rho_d = \frac{\rho_{wet}}{1 + w} \tag{4}$$

8) Outline of the Proctor Curve

A curve can be traced on the basis of actual water content and dry density of the material. The curve takes a characteristic convex shape [6]. The aim of this curve is to determine maximum dry density and the optimum water content for the material. Generally, the optimum (point where dry density is maximum and the corresponding water content is the content at which the material must be treated in situ to comply with mechanical criteria) is between the two saturation curves Sr=80% and Sr=100% [7]-[9].

9) Immediate Bearing Capacity Measurement

To measure IBI, we placed a collar on the CBR mould because the punch must be applied to the centre of the sample. We increase the force applied by the punch (in kN) in relation to the depth of the punch (in mm). Thus, permitting determination of IBI whose value is defined by:

$$IBI = Max\left(\begin{array}{c}\frac{\text{Force at 2,5mm penetration depth (kN)}}{13,35} * 100\% \\ \frac{\text{Force at 5 mm penetration depth(kN)}}{19,93} * 100\%\end{array}\right) \qquad (5$$

IV. MECHANICAL CHARACTERIZATION OF THE TREATED SEDIMENTS

A material can be used for earthworks if its load bearing capacity can support acceptable movement of heavy machinery. This type of application generally concerns soils that are sensitive to water which such soil in a wet state. To make subgrades, the requirements are higher and the mechanical performance of the treated material must be studied [8].

A. Evaluation of the Suitability of a Soil for Treatment

Mechanical performance studies are often lengthy, but the suitability of a soil for the planned treatment must be determined quickly. Special types of conservation make it possible to ensure, within a relatively short time (two weeks maximum) that the material treated after compaction presents dimensional stability and mechanical behavior in line with expectations.

The treatment suitability test described in standard NF P94-100 [10] consists in accelerating hydraulic setting. It is carried out on cylindrical tensile specimens 1 (Dxh = 5x5 cm) with storage procedures described in Table IV.

TABLE IV
STORAGE PROCEDURES

Type of treatment	Storage procedure
Treatment with lime alone	3 days ± 4 hours at 20 ± 2°C and over 90% humidity followed by immersion for 7 days ± 4 hours in water at 40 ± 2°C
Treatment with a hydraulic binder (*) associated with lime where applicable	4 days ± 4 hours at 20 ± 2°C and over 90% humidity followed by immersion for 7 days ± 4 hours in water at 40 ± 2°C

(*): Storage time at 20 ± 2°C and at over 90% humidity must be between 1.5 and 2 times workability time in the case of treatment with a hydraulic road binder (HRB).

In relation to the products used, the parameters to consider are volumetric swelling (GV) and where applicable, the level of mechanical strength. For lime treatment, only the swelling effect that can be developed is monitored. For treatment with binder alone or with lime, in addition to swelling, mechanical strength (Rit) is evaluated through indirect traction resistance tests after 7 days of immersion. Different reference values show the suitability of the soil for the treatment (Table V).

TABLE V
ASSESSMENT CRITERIA FOR EVALUATING THE SUITABILITY OF SOIL FOR TREATMENT WITH LIME AND/OR HYDRAULIC BINDERS (NF P 94-100) [10]

Type of treatment	Soil suitability	Parameter considered	
		Volumetric swelling GV (%)	Indirect traction resistance Rit (MPa)
Treatment with a hydraulic binder, associated with lime where applicable	suitable	≤ 5	≥ 0.2
	doubtful	5 ≤ GV ≤ 10	0,1 ≤ Rit ≤ 0,2
	unsuitable	≥ 10	≤ 0.1
Treatment with lime alone	suitable	≤ 5	Parameter not considered for this type of treatment because of the slowness of pouzzolanic reactions
	doubtful	5 ≤ GV ≤ 10	
	unsuitable	≥ 10	

B. Evaluation of Mechanical Performance

The use of a treated soil in subgrades must meet the following criteria in the more or less long term [11]:

- age when the treated layer can support traffic,
- resistance to immersion at a young age,
- frost resistance,
- assumed long-term performance.

Two reference mechanical tests are used to assess these criteria. The first test, determination of unconfined compressive strength (RC), that is the breaking strength of specimens with dimensions Dxh = 5x10 cm, characterizes the short term behavior of the material. The second test enables a study of long term behavior and to size the structure. It consists in evaluating the indirect traction resistance (Rit) and the elastic modulus (E) on specimens Dxh = 5x5 cm.

1) Short-Term Behavior

That is, the age at which construction machinery can circulate on the treated layer which is simulated by immersion resistance tests at a young age and frost resistance.

The first two points constitute the criteria of trafficability and insensitivity to water respectively. The trafficability criterion is deemed satisfactory when unconfined compressive strength (R_C) is over 1.0 MPa [12]. Insensitivity of the material to water consists in comparing resistance obtained at 60 days on specimens subjected to two different types of treatment. For the first series of specimens, they are normally kept in hermetic cells for 60 days and correspond to R_{C60} after crushing. The second series, after 28 days of normal treatment, is immersed in water at 20 °C for 32 days, and after crushing, gives RCi60. The ratio RCi60/RC60 permits evaluation of the material's insensitivity to water. Insensitivity is satisfactory if:

- **Rci60/Rc60>0.80** when the BVS of the soil is ≤ 0.5
- **Rci60/Rc60>0.60** when the BVS of the soil is > 0.5

Frost resistance is defined by a minimum value of indirect traction resistance. The material treated is considered frost resistant if the value of Rit at the age corresponding to the first possible statistical appearance of frost is greater than 0.25 MPa. Frost resistance can also be evaluated with a frost swelling test following standard NF P 98-234-2 [33].

2) Long-Term Behaviour

The long-term mechanical behavior of a treated soil is characterized by the indirect traction resistance test. Described in standard NF P 98-232-3 [15], it permits determination of the pair (Rit; E) required to size the subgrade. Table VI presents a summary of the requirements for using material treated with hydraulic binders in subgrades.

TABLE VI
MECHANICAL CHARACTERISTICS REQUIRED FOR TREATED SOIL USED IN SUBGRADE (LCPC-SETRA, 2000) [21]

Considered aspect of treated soil behaviour	Representative mechanical characteristics	Evaluation criteria
Age authorising circulation on the treated layer	RC at 7 and 28 days	The subgrade can take traffic when RC ≥ 1.0 MPa
Resistance to immersion at a young age	Rt or Rit measured at the age of the treated soil corresponding to the likely date of the appearance of frost on the site in question	Resistance to immersion at a young age is deemed satisfactory: Rci60/Rc60>0.80 when the BV S of the soil is ≤ 0.5 Rci60/Rc60>0.60 when the BV S of the soil is > 0.5
Frost resistance	Rt or Rit and elastic modulus E measured at 28 and 90 days and if necessary, at 180 days in the case of slow setting HRB	Frost resistance is considered satisfactory if the value of Rit at the age corresponding to the first possible statistical appearance of frost is greater than 0.25 MPa.
Assumed long-term performance		The pair (Rt, E) determined at 90 days (or possibly at 180 days in the case of a slow setting binder) leads to at least a mechanical class 5 material.

C. Sizing the Subgrade

When the mechanical requirements have been satisfied the subgrade can be sized. Sizing is done based on the upper part of earthworks-subgrade pair constituting the support platform for the road. More precisely, the thickness of the subgrade depends firstly on the type of upper layer and the long-term bearing capacity of the roadbed (RB) and secondly, on the long-term mechanical characteristics of the material in the subgrade [13].

When the mechanical class of the material and the roadbed has been determined, the thickness of the subgrade can be defined. Knowledge of these three parameters can attribute a class to the platform (PFi).

Long term mechanical performances, that is, knowledge of the pair (Rit; E), mean the material can be classified according to the different abacus calculated fields. Traction resistance Rt is evaluated using Rt = 0.8 Rit (Fig. 7). In relation to this classification and following the mode of manufacture (at the plant or on site), it is attributed a mechanical class (from 1 to 5) (Table VII).

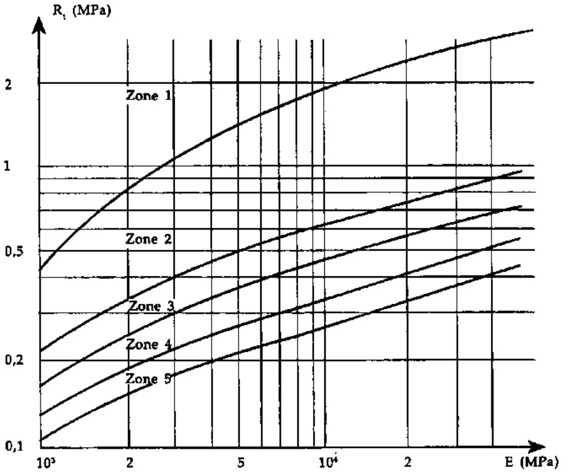

Fig. 7 Classification areas of the material according to its traction resistance Rt and elastic modulus E (LCPC-SETRA, 2000) [21]

TABLE VII
MECHANICAL CLASS OF A MATERIAL TREATED IN RELATION TO ITS LONG TERM CHARACTERISTICS AND PRODUCTION PROCESS [2]

Treatment at the plant	Treatment in situ	Mechanical class of the material
area 1	-	1
area 2	area 1	
area 3	area 2	3
area 4	area 3	4
area 5	area 4	5

Table VII gives the different classes of platform in relation to the type of roadbed, the mechanical performances of the treated material and the thickness of the subgrade.

TABLE VIII
DETERMINATION OF THE CLASS OF PLATFORM IN RELATION TO THE TYPE OF ROADBED, THE MECHANICAL PERFORMANCES OF THE TREATED MATERIAL AND THE THICKNESS OF THE SUBGRADE [21]

Mechanical class of the subgrade material	Thickness of the subgrade layer				
class 3	-	30 cm	40 cm	25 cm	30 cm
class 4	30 cm	35 cm	45 cm	30 cm	35 cm
class 5	35 cm	50 cm	55 cm	35 cm	45 cm
Class of platform obtained	PF2	PF3	PF4	PF3	PF4

D.Equipment and Materials

- Equipment
  - Two scales
  - Hammer
  - PVC "moulds"
  - System for producing specimens with static compression: static compressor
- Materials
  - Dry sediments
  - ROLAC® 645
  - Water

E. Experimental Protocol

Following standard NF P98-114-3 (2001) [14], specimens 100 mm in length and 200 mm in diameter (the volume is therefore known 196.35 cm^3) are used for mechanical tests, considering that the maximum size of the materials is below 20 mm. The protocol for producing specimens by static compression, the description of the moulds and the normal storage procedures are specified in standard NF P98-230-2 [22].

The amount of wet material in each specimen is calculated based on the following equation, after determining dry density and the desired water content. The specimens must be kept in a hermetic plastic box at 20 ºC.

$$M = \frac{V \times \rho_d \times (100 + w)}{100} \qquad (6)$$

with M: Theoretical mass of the specimen on production (g); ρ_d : Established dry density (g/cm^3) upon production of the specimen (g/cm^3); V: Specimen volume (cm^3); w: Water content established when preparing the specimen (%).

The mould has three parts: Two caps and a slotted cylinder in the middle. Before putting the specimen in the compressor, the cylinder must be taped to make it water tight, putting the cap on the bottom and taping it as well.

The mould must be filled with treated or untreated sediments before the specimen is put in the compressor. The ideal calculated weight is around 3600 g. Finally, the machine is started to compact the sediments statically.

When the specimen has been compacted, it is immediately removed from the mould and placed in plasma. These specimens, with a water content of around 7.8-8% and ROLAC® contents of 6% and 8%, permit mechanical tests on the treated sediments.

V. RESULTS

A. Compaction and IBI

Proctor compaction characteristics are very useful parameters for identifying materials and defining the applicable compaction specifications when they are used to construct embankments and subgrades. The principle of these tests consists in compacting the materials to various water contents according to a given energy according to standard NF P94-093 (1999) [6].

The materials, previously mixed with a certain amount of water are placed in the CBR mould in 5 layers. Between each addition, the layer is compacted with a tamper following the protocol of 56 blows per layer, applied in series of 7 blows. At the end of the test, the collar is withdrawn and the surface of the mould is levelled. Knowing its mass and volume (standardized dimension: diameter= 152 mm, height= 126.6 mm) it is possible to determine the wet density (WD) and dried density (DD) of the compacted material. Based on this relationship between dry density and water content, the characteristics of the formulated materials, that is maximum dry density and optimum water content, can be determined.

In addition to the compaction tests, the immediate bearing capacity (IBI) can be measured The IBI is conventionally defined to evaluate the suitability of a soil or a man-made material to withstand heavy machinery moving over it. The immediate bearing index of a compacted soil is determined by a punch test with a 19.3 cm 2 cross-sectional piston, rammed in at a constant speed of 1.27 mm/min, according to standard NF P94-078 (1997) [24]. Conventionally, the IBI is the larger of the following 2 values:

- (Penetration effort at 2.5 mm depth (in KN) x100)/13.35.
- (Penetration effort at 5.0 mm depth (in KN) x100)/20.

This test was initially performed on raw sediments. In view of the results, we decided to treat them with 6% ROLAC® 645, followed by an 8% dose.

In Figs. 8-10 are examples of the modified Proctor-IBI curves and a summary of the mechanical parameters for the three formulations.

Table IX summarizes the mechanical parameters of the formulations. Figs. 10, 11 resemble the modified Proctor test and IBI results for the raw sediments and sediments treated with 6% and 8% of binder. It can be seen that density and IBI vary in relation to water content.

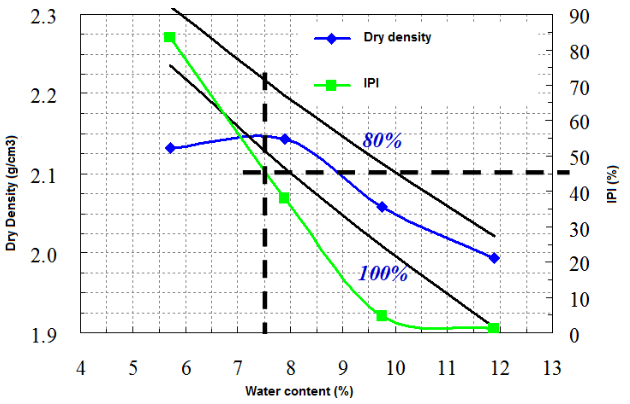

Fig. 8 Dry density curve - water content - IBI for raw sediments

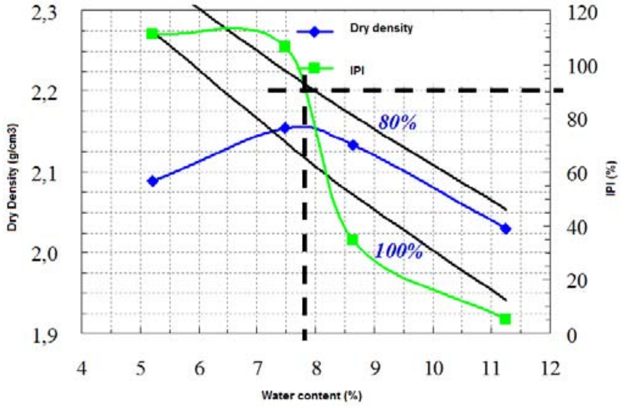

Fig. 9 Dry density curve - water content - IBI for treatment with 6% ROLAC® 645

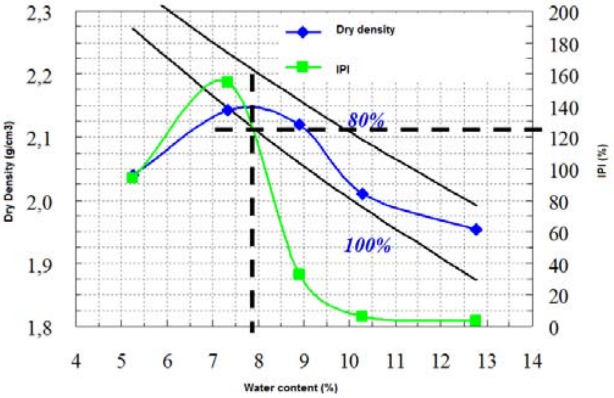

Fig. 10 Dry density curve - water content - IBI for treatment with 8% ROLAC® 645

TABLE IX
MECHANICAL PARAMETERS OF FORMULATIONS

Materials	SD	SD6R	SD8R
Maximum dry density (g/cm^3)	2.147	2.155	2.148
Optimum water content (%)	7.5	7.8	7.9
IBI (%)	45.3	90.1	124.6

Table IV shows that treatment with ROLAC® 645 has a significant impact on optimum water content and IBI and a weak impact on maximum density in raw sediments. In fact, a treatment of 6% ROLAC®645 achieves an increase of around 100% in IBI and a 0.4 point increase in water content in relation to raw sediments. With a treatment of 8% ROLAC®645, the IBI value increases from 90.1% to 124.6% with little variation in water content and density. It can be seen that increasing the ROLAC®645 content can considerably improve immediate bearing capacity. This result is particularly satisfactory as the GTR (Guide to Road Earthworks) imposes a minimum IBI of 25% for use as a subgrade and a minimum IBI of 35% for use as a foundation layer.

1) Long-Term Mechanical Performance

In addition to the IBI values, the formulations must have sufficient mechanical characteristics to ensure that the road functions well. This capacity is evaluated by two mechanical tests. These tests consist in crushing the cylindrical specimens (accomplished in this study using vibro-compression).

- Unconfined compression
- Indirect tensile strength
- These two tests lead to determine two mechanical parameters which are:

– The deformation modulus (Em)
– Traction resistance (Rt)

These tests were performed on 28-day old samples. From the empirical coefficients the parameters for 360 days of treatment can be deduced as imposed by classification of the materials.

B. Determination of the Deformation Modulus

The deformation modulus linked to the stress and deformation of a standard specimen in the elastic region following Hooke's law:

$$\sigma = E * \varepsilon \tag{7}$$

The following equipment was used for this test:

- A press
- A press control unit linked to the control software on the computer
- An extensometry system equipped with sensors
- Force sensor
- A data acquisition system

In order to evaluate the feasibility of using mixtures produced in the roadbed layer, the results must be positioned in the abacus calculation based on the data (Rt and E). Note that the reference values for classifying the materials are defined after 360 days of normal curing. When the period does not allow measurement at 360 days, the elastic modulus and traction resistance at 360 days can be determined using the empirical formula for the values at 28 days or 90 days in relation to the type of binders used.

In our case, the formulations were used after 28 days of curing. Based on standard NF P98-113 (1994) [23] and NF P98-114-2 (2009) [25], mechanical parameters at 360 days are calculated respectively using the formulas for sediments treated with ROLAC®645. The results in the abacus classification below are mean values from three specimens. Empirical relationships enable determination of the deformation modulus at 90 and 360 days. For each formulation, three tests have been carried out.

$$\frac{E_{28\,days}}{E_{360\,days}} = 0.65 \qquad \frac{E_{28\,days}}{E_{360\,days}} = 0.75 \tag{8}$$

C. Determination of Traction (and Compressive) Resistance

The aim of the traction study is to determine mechanical performances: Traction resistance Rt and elastic modulus E at 28 days of maturation. The pair (Rt, E) is evaluated with the Brazilian traction text described in standard NF P98-232-3 (1993) [15] on cylindrical tensile specimens 2. The traction test principle consists in determining indirect tensile strength by applying a linear load on 2 diametrically opposed generators on the cylindrical specimen. Traction resistance is given by the resistance to compression (by a press). In fact, these two parameters are connected by

$$R_t = 0{,}8 * R_{t_b} = 0{,}8 * 2 * 10^{-2} * \frac{F_r}{\pi \o h} \tag{9}$$

where R_{tb}: Diametric compressive strength (MPa); R_t: Traction resistance (MPa); F_r: Applied force at the failure (MPa); ϕ: Diameter of sample (cm); h: Height of sample (cm).

D. Results of the Two Tests

Fig. 10 shows the results of each test and the mean value calculated with the equation: 6% ROLAC®645, w_{opt}=7,8%.

The compression tests permit determination of the age authorizing the circulation of heavy machinery on the subgrade compression resistance is evaluated after 14, 28, 60, 90 and 360 days of normal maturation. The trafficability criterion is deemed satisfactory when unconfined compressive strength (R_C) is over 1 MPa. The idea is use evolution curves to estimate the evolution of the time required to verify this condition. The results at 28 days for sediments treated with ROLAC®645 are shown in Table X. Two samples at least are taken of each formulation and each curing period, the resistances reported are the average values calculated from 3 specimens.

Table X presents a comparison of all the data obtained on the treated sediments. A gain in compressive resistance is observed in the treated sediments for all the substitution rates in relation to raw sediment. However, the inclusion of lime does not bring any significant improvement in compressive resistance. Among the sediment-ROLAC®645 formulations, 6% lime is the best choice from a financial point of view. Compressive resistances for all the sediments treated with quick lime are below 1 MPa for all curing periods.

As regards treatment with cement, compressive resistance of the formulations increases with an increase in the amount of cement and the curing period. For the SD3C formulation, it appears that resistance is almost constant for a curing period of 14 days to 90 days. For the formulations SD6C and SD9C, compressive resistance develops noticeably in relation to time. For sediments treated with cement, all compressive resistances (4.67 and 5.92 MPa for 6% and 8% ROLAC®645) are greater than 1 MPa. Thus a subgrade is trafficable when its compressive resistance is greater than 1 MPa.

TABLE X
COMPRESSIVE STRENGTH

Formulation	SD6R (MPa)	SD8R (MPa)
1	4.77	6.14
2	4.57	5.70
3	3.69 (Abnormal)	---
Mean (MPa)	4.67	5.92

In order to evaluate the feasibility of using mixtures produced in the roadbed layer, the results must be positioned in the abacus calculation based on the data (Rt and E). Note that the reference values for classifying the materials are defined after 360 days of normal curing. When the period does not allow measurement at 360 days, the elastic modulus and traction resistance at 360 days can be determined using empirical formulas for the values at 28 days or 90 days in relation to the type of binders used.

For all the formulations (SD6R and SD8R) all the tests (and in fine, the mean) are in class S2. A subgrade requires a formulation of a class equal to or higher than X1, but the foundation layer requires a formulation of a class equal to or higher than X2. Furthermore, an IBI equal to or higher than 25% or 35% is required, which is largely the case of the formulations "sediments treated with 6% binder, and optimum water content" (IBI=90.1%) and "sediments treated with 8% binder, and optimum water content" (IBI=124.6%). Thus, we can deduce that sediments treated with 6% and 8%

ROLAC®645, at the Proctor optimum (that is a water content of around 7.8%) can easily be used for road building and especially in subgrades.

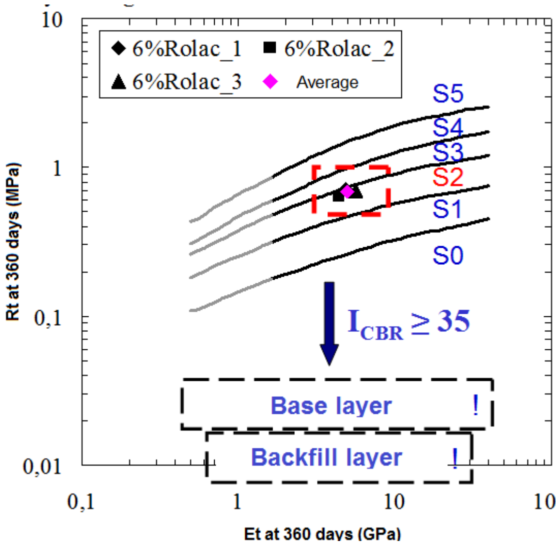

Fig. 11 Elastic modulus and traction resistance results at 360 days (sediments treated with 6% ROLAC®645)

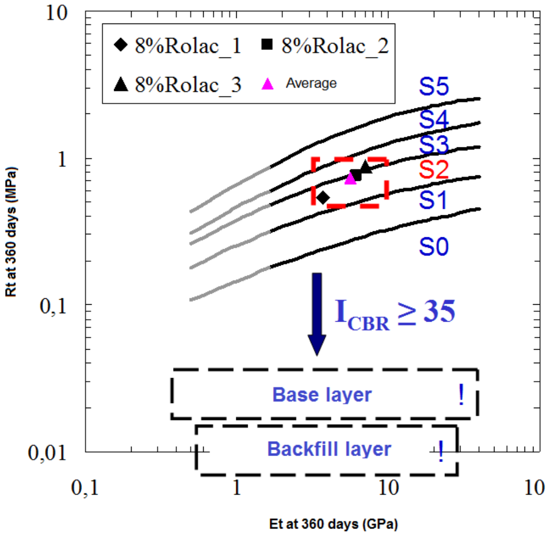

Fig. 12 Elastic modulus and traction resistance results at 360 days (sediments treated with 8% ROLAC®645)

TABLE XI
CLASSIFICATION CRITERION

Nature of the layer	Class
Base layer	$\geq S_2$
Foundation layer	$\geq S_2$
Subgrade	$\geq S_1$

After analysis of the results, it is interesting to note that the evolution in compressive resistance is practically identical to that of traction resistance. In relation to the different treatments, evolutions and performances are noticeably different. In fact, the C-S-H formation delivers the best mechanical performances at 28 days [16], [17].

VI. CONCLUSION

In this paper, the use of raw sediment or lime and cement treated sediment as a base layer for roadway is studied. It is established some treatment methods can induce physical and chemical modifications.

It was performed multiple tests that lead to conclude that mechanical resistance of materials based on ROLAC®645 is significant. This proves that the ROLAC®645 may be used for a suitable treatment. The measure of mechanical resistance (traction, compression, modulus, etc.) leads to infer that treated material with ROLAC®645 can be used in subgrades and foundation layers for roads.

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