Valorisation des sédiments de dragage en techniques routières.

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ABSRACT

Nowadays, more than 90 % of the economic exchanges are performed by sea channels. In order to improve the harbor infrastructures, ports managers organize dredging and clearing out operations which generate a large quantity of sediments. A volume of 1.6 million m^3 of harbor sediments is dredged every year on the French Channel ports to maintain a certain water depth (setarms.org, 2015). These important volumes of sediments must be managed according to the new environmental rules that sediments is considered as waste because of its high content and leachability of heavy metals, organic matter (humic and fulvic acids) and soluble salts (European directive number 75/442/CE JOCE, 1975). In France the annual consumption of natural aggregates extracts from quarries exceeds 400 MT and on another side this resources are becoming scarce for civil engineering applications. One of the innovative solutions for dredged sediments management is their reuse as alternative material in road construction. Due to its perpetual availability, their mineralogical composition, and geotechnical characteristics, sediments are considered a suitable raw material for reuse as construction materials. According to the recent studies (Hake, 2003; Rekik et al., 2006; Dubois et al., 2006; Maherzi et al., 2010;) conducted on treated sediments with hydraulic binders (lime, cement or fly ash). Dredged sediments are characterized by their high initial water content and high organic matter content, these factors can be problematic for their reuse in their raw state as materials for road construction. In order to improve sediments characteristics, addition of a granular corrector as sand, blast furnace slag or bottom and fly ash and hydraulic binder treatment is recommended (Colin, 2003, Dubois et al., 2008; Miraoui et al., Tran, 2009; Boutouil et al., 2011; Wang *et al.*, 2011; 2012; Yan et al., 2014). In these mentioned studies the rate of sediments in the mixtures was minority and did not exceed the 40% of the dry mass of the mixture. This is considered as insufficient to enhance the large volumes of sediments dredged annually.

Furthermore, existing studies on reuse of dredged sediments as pavement layers focused on the short term mechanical strength without considering the

sustainability parameters: porosity, water aging, volumetric swelling, and freeze thaw. The Technical French Guide for soils treatment with lime and/or hydraulic binders GTS (LCPC-SETRA, 2000) prescribed sustainability tests to achieve measurement of the volume swelling and indirect tensile strength of treated materials, to reproduce the effect of a possible rise of the underground water. These sustainability parameters are strongly influenced by the interaction between sulfates presenting in sediments and ettringite provided from cement hydration, in case of the presence of water.

Keywords: sediment, mechanical strength, swelling, SEM analyses, suitability tests,

1. INTRODUCTION

In this study we integrated the influence of the type of binder and their dosage on mechanical and durability parameters properties of materials based on a large fraction of marine dredging sediments. In fact, two types of hydraulic binders based on different mineral composition were tested. In order to suitability tests and mechanical performance of different designed materials were investigated according to the Technical Guide for Treatment of Soils with lime and/or hydraulic binders–application to the construction of embankment layers (SETRA-LCPC, 2000). The main purposes are to: determine the compaction references of designed materials, investigate the compressive and tensile strengths of treated sediments with cement, and evaluate their potential reuse as backfill materials analyze the durability of solidified of designed and finally SEM analyses of treated mixtures.

2. MATERIALS

2.1. Sediments

The studied sediment is from the port of Brest located in North West France. The port of Brest, located at the crossroads of major sea currents on one of the most beautiful bays in the world. In 2015 the port of Brest has achieved 2.5 Mt of merchandise trade. Ensure an acceptable level of service the Brest port managers conducted regularly dredging operations, which generate very large volume of sediment. Generally these sediments are stored in specific facilities dedicated to waste management. In this experimental study dredged sand was used as granular corrector to evaluate its influence on the packing density and on mechanical performance of mixtures (Miraoui et al., 2012). There was provide from a dredging operation for the creation of new port areas.

Figure 1. Location of Brest port

2.2. Hydraulics binders

To ensure a better mechanical strength and better insensitivity to water, the mixture should be treated with cement. Indeed, in this study two road hydraulic binders were used, referred as C1 and C2. These hydraulic binders were primarily composed of clinker. The chemical and mineralogical characteristics of these two binders are shown in Table 4. Their mineralogical composition also based on fluxing (Fe_2O_3, CaO, MgO, K_2O and Na_2O) and glass forming oxides (SiO_2, Al_2O_3) would ensure the development of CSH and CAH gel.

Table 1. Characteristics of the two hydraulic binders

cement	Mineral composition (%)	
	C1	C2
C_3S	62	66
C_2S	12	11
C_3A	12	7
C_4AF	6	10
	Elementary chemical composition	
SiO_2	19.10	20.79
Al_2O_3	4.50	5.40
Fe_2O_3	2.90	2.22
CaO	62.00	65.90
MgO	1.30	1.10
K_2O	1.56	0.30
SO_3	3.00	3.40
Na_2O	0.20	0.18
Cl^-	0.02	0.03
S+A	23.60	26.19
Fluxing	67.96	69.70

Note : S+A=SiO_2+Al_2O_3 and fluxing= Fe_2O_3+CaO+MgO+K_2O+Na_2O

3. METHODS

3.1. Experimental protocol

The physical and characterization tests of raw sediment , such as grain size distribution, the initial water content, the organic matter content, the specific gravity, Plasticity index, Methylen Blue Value were conducted according to European and French standards (for details, see Maherzi, 2013). Characterization of the effect of the two different hydraulic binders in the treatment on the mixtures was based on two types of tests: testing of mechanical performances (Standards Proctor References, Unconfined Compression Strength 'UCS' and Indirect Tensile Strength 'ITS') and sustainability testing (Volumetric Swelling., ITS after immersion).

3.1.1. Mechanical characterization

First, the Mechanical performance of treated materials were investigated through Normal Proctor test and Immediate Bearing Index 'IBI' according to the European EN 13286-2 (2010) and French standards NF P 94-093 (1997), respectively. The mixtures were prepared according the European standard EN 14227-11 (2006), which described in Fig.2. The results of the Standards Proctor test (w_{OPN}, ρ_d) allowed the preparation of test samples for mechanical performance and sustainability testing investigation according to the European standards EN 13286-53 (2000). The samples were conserved in hermetic moulds for 7, 28, 60 and 90 days, at a temperature of 20°C, before mechanical testing. The unconfined compression strength (UCS) test was carried out according to the European standards (NF EN 13286-41) and the indirect tensile strength (ITS) tests were carried out according to the European standards (EN 13286-42; EN 13286-43).
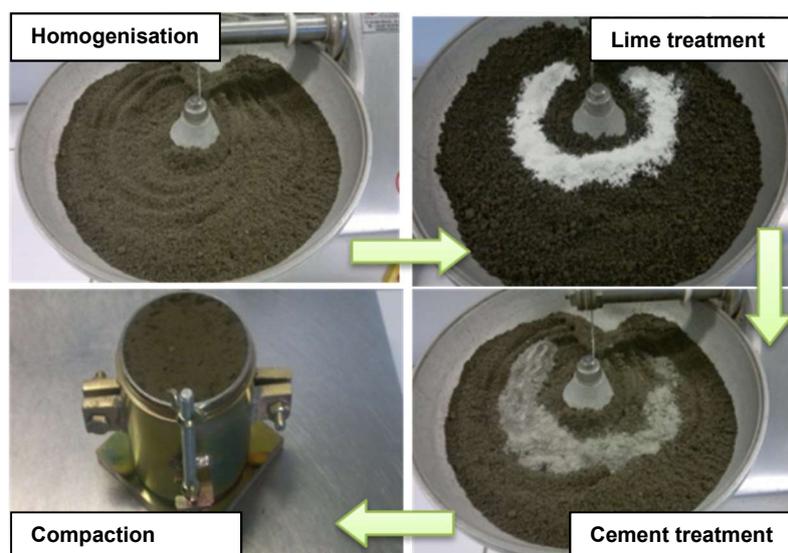

Figure 2. Preparation of treated mixtures.

3.1.2. Sustainability characterization

To evaluate the sustainability of treated materials, the volumetric swelling tests and indirect tensile strength after immersion in water at 40°C during 7 days were performed according to European and French standards (NF P 94-100; EN 13286-49; EN 13286-42). Specimens testing were placed at 20°C and 90% relative humidity for 4 hours, than they were immersed in water at 40°C for 7 days (Fig.3). The results were interpreted on the basis of criteria set out in table 7. To validate the applicability of the sediment mixture treatment on road construction, the results obtained were compared with the criteria for reuse as fill materials according to the Technical French Guide 'GTS' (SETRA-LCPC, 2000).The flowchart, shown in Fig.4, summarizes the experimental procedure adopted in this study.

Tableau 2. Criteria for interpreting sustainability of treated materials

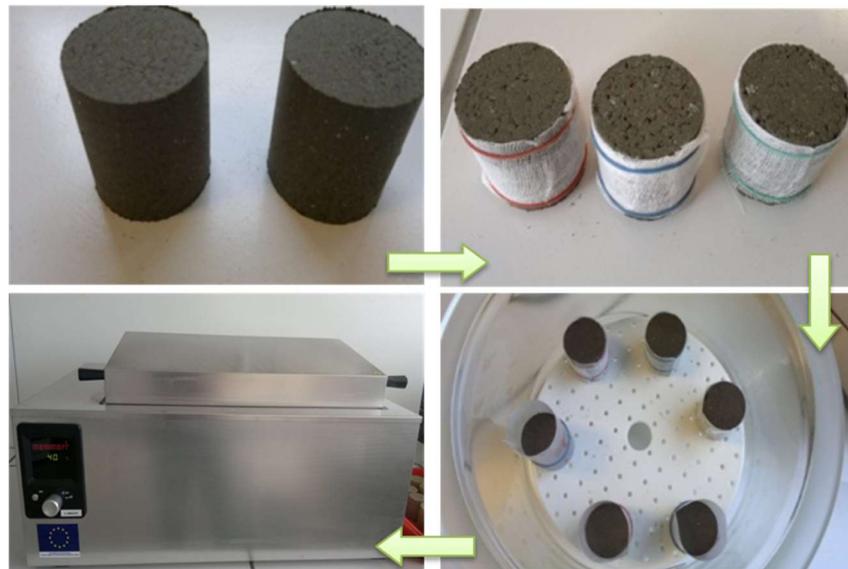|	After conservation in water at 40°C during 7days	
	Volumetric swelling (%)	Indirect Tensile Strength (MPa)
Suitable	V.S.<5 and ITS>0.2	
Doubtful	$5 \leq$ V.S.≤ 10 or $0.1 \leq$ ITS≤ 0.2	
Unsuitable	V.S.>10 or ITS<0.1	

Figure 3. Sample conditioning techniques for ability tests

3.1.3. Suitability criteria for embankment materials

To validate the applicability of the sediment mixture treatment on road construction, the results obtained were compared with the criteria for reuse as embankment materials according to the Technical French Guide 'GTS' (SETRA-LCPC, 2000). The flowchart, shown in Fig.4, summarizes the experimental procedure adopted in this study.

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                         ┌─────────────────────────────┐
                         │      Testing procedure      │
                         └─────────────────────────────┘
                │                                       │
   ┌────────────────────────┐              ┌────────────────────────┐
   │  Sustainability criteria│              │  Solidification criteria│
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Testing procedure

Sustainability criteria | **Solidification criteria**

Proctor normal test (w_{OPN}, ρ_d) and immediate bearing ratio (IBI)>20

Samples preparations with static compression:
Volumetric swelling (VS) specimen's tests (5x5) cm and ITS specimen's tests (5x5) cm: three specimens for each test

Samples preparations with static compression:
UCS specimen's tests (5x10) cm and ITS specimen's tests (5x5) cm: three specimens for each test

Curing conditions:

Relative Humidity > 90% and temperature 20°C for 4h±15min then immersion in a bath at 40°C for 7days before testing

Curing conditions:

Relative Humidity > 90% and temperature 20°C for 7, 28, 60 and 90days before testing.

VS tests | **ITS tests**

ITS tests | **UCS tests**

Suitability to treatment criteria:

ITS > 0.20 MPa
and
VS < 5%

Traficability criteria:

Age corresponding to UCS ≥ 1 MPa

Freezing resistance criteria:
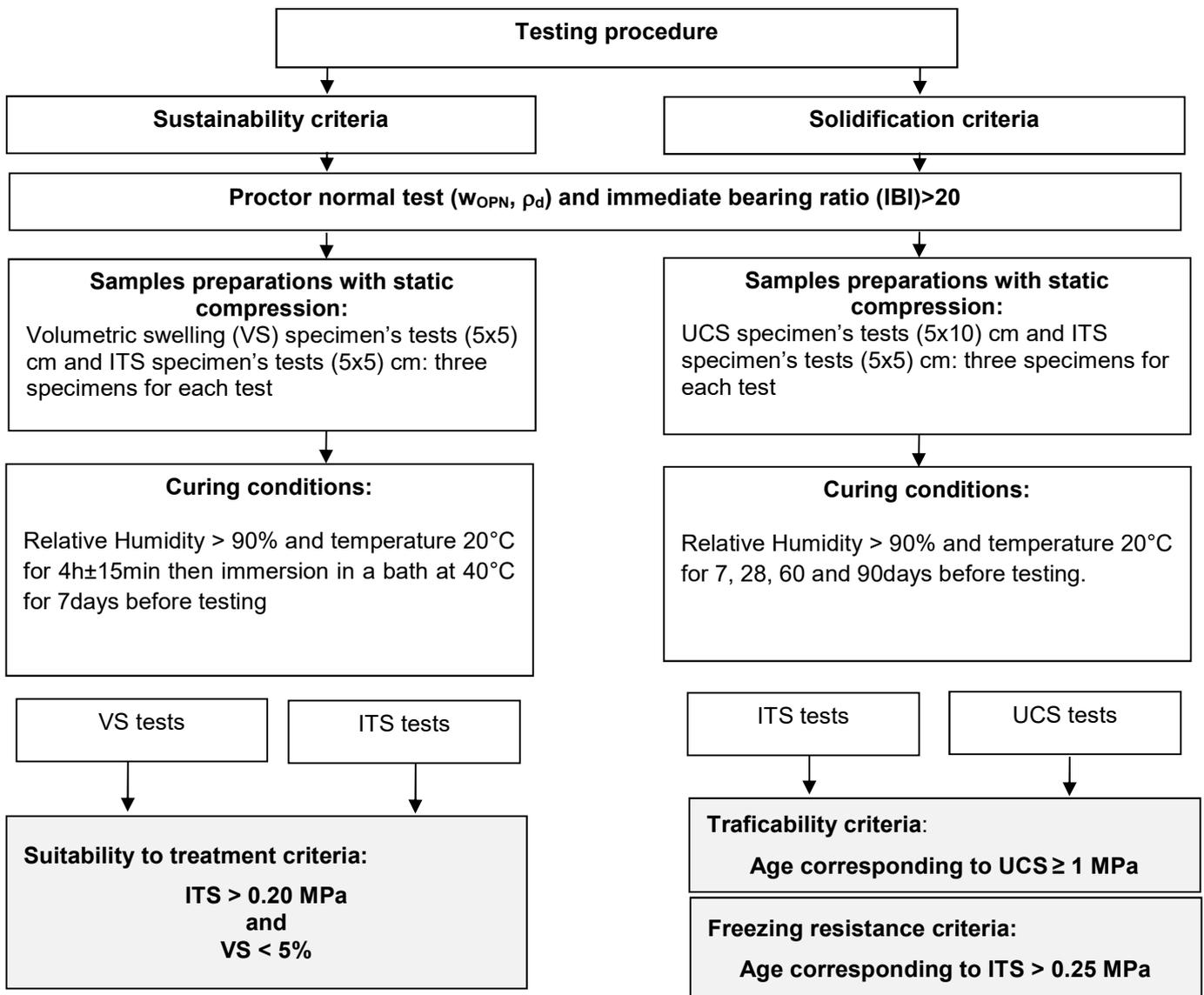
Age corresponding to ITS > 0.25 MPa

Figure 4. Preparation of the specimens for experimental investigation

4. Results and discussions

In this part all tests were run in three times and standard deviation of measurements does not exceed 0,1.

4.1. Raw sediments characterization

4.1.1. *Physical characteristics*

Table 5 present the results of physical characterization of raw sediment. It appears that the sediment of the port of Brest was fine material with significant organic matter content. According to the GTR guide (1992) it was classified in F class, which includes organic soil and industrial waste. The results are in agreement with previous studies performed on sediment for various origins (Colin, 2003; Rekik

et al., 2009; Zentar et al., 2008; Kamali et al., 2008; Zentar et al., 2008; Dubois et al., 2009; Sillitonga, 2010; Boutouil et al., 2011; Zentar et al., 2012; Miraoui et al., 2012; Bel Hadj Ali et al., 2014; Achor, 2014). The valorization of these materials in road construction applications such as embankment materials should be achieved using treatment with hydraulic binders to improve their mechanical behavior (LCPC-GTS, 2000).

Table 3. Physical characteristics of the studied sediment

Sediment parameter	Standards	Value
Moisture content (%)	EN 1097-5	95
Organic matter Value(O.M.C)	EN 15169	5.40
pH	NF ISO 10390	7.6
Clay fraction (0/2 µm)		19.60
Silt fraction (2/63 µm)	ISO 13320-1	31.40
Sand fraction (63 µm/2 mm)		49
Fine fraction (0/80 µm)		77
Absolute density ρ_s (mg/m^3)	NF P 94-054	2.53
Liquid limit (W_L)	NF P 94-051	57
Plasticity index (IP)	NF P 94-051	20
Methylen Blue Value (g/100 g dry)	EN 933-9	1.40
GTR classification	**NF P 94-100**	**F_{11}**

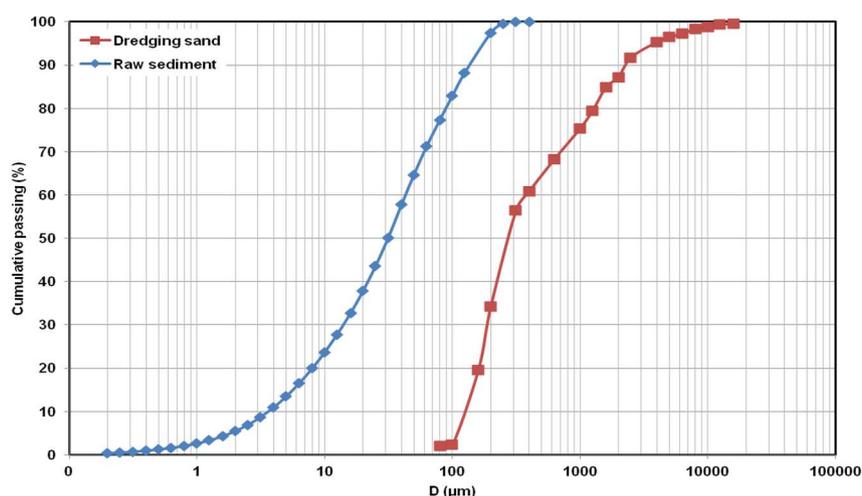
Fig. 5. Grain distribution curves of the granular addition and raw sediment

4.1.2. Mineralogical characteristics

The mineralogical composition of the < 2mm fraction of the dredged marine sediment was determined by automated mineralogy (QEMSCAN®) using sample preparation (polished mounts) and data processing techniques described by Pirrie

and Rollinson (2011) and Rollinson et al. (2011). Particle mineralogical analysis mode was applied to the samples and 2.7 million X-ray analysis points at pixel spacing of 2 to 5 μm (coarse and fine fractions) provided the chemical information from which the mineralogy was inferred. The percent mineral volumes for the sediment are presented in Table 7. The primary minerals comprising a percent mineral volume of approximately 85 % were carbonates, feldspars, quartz and other silicates. A pyrite composition of 1.72 % was also determined. This value is high compared to sediments dredged from other ports which have been found to range from 0.06 to 1.42 % (van Veen, 2013). The average grain size of the pyrite grains detected in the sample was small than 8 μm. These small pyrite particles are typical of framboidal pyrite (figure 1-D); minute raspberry shaped spherical pyrite formations found in natural sediments (Ohfuji and Rickard, 2005).

Table 4. Percent mineral volumes for the raw dredged marine sediment

Mineral category	Mineral composition	Mineral volume composition (%)
Pyrite	FeS_2	1.76
Carbonates	$CaCO_3$	25.30
Feldspar	$(Ba,Ca,Na,K,NH_4)(Al,B,Si)_4O_8$	22.50
Other silicates	-	20.60
Quartz	SiO_2	16.70
Mica/Illite	$KAl_2(Si_3Al)O_{10}(OH,F)_2$	6.79
Al silicates	Al_2SiO_5	2.42
Fe Al silicates	$Fe\ Al\ SiO_3$	2.18
Gypsum	$CaSO_4$	1.04
Rutile	TiO_2	0.28
Fe-Ox/CO3	-	0.19
Halite	$NaCl$	0.09
Others	-	0.08
Ilmenite	$FeTiO_3$	0.03
Apatite	$Ca_5(PO_4)_3(OH,Cl,F)$	0.02
Zircon	$ZrSiO_4$	0.02
Titanite	$CaTi(SiO_5)$	0.01

4.1.3. Environmental characteristics

Table 5.

		N1	N2	Sed. Brest
	Total Organic Carbon (% MS)	-	-	2.2
Heavey metals (mg/kgMS)	As	25	50	<25
	Cd	1.2	2.4	<0.4
	Cr	90	180	31.9
	Cu	45	90	73
	Hg	0.4	0.8	<0.1

	Ni	37	74	22.9
	Pb	100	200	61.3
	Zn	276	552	136.8
Polychlorinated biphenyls (mg/kg MS)	PCB 28	0.025	0.05	<0.007
	PCB 52	0.025	0.05	0.009
	PCB 101	0.050	0.10	0.017
	PCB 118	0.025	0.05	0.012
	PCB 138	0.050	0.10	0.023
	PCB 153	0.050	0.10	0.027
	PCB 180	0.025	0.05	0.013
Polycyclic aromatic hydrocarbons (mg/kg MS)	Benzo(a)pyrene	0.20	1	<u>0.34</u>
	Benzo(b)fluoranthene	0.30	3	<u>0.32</u>
	Benzo(ghi)perylene	0.20	1	<u>0.25</u>
	Benzo(k)fluoranthene	0.20	2	0.17
	Fluoranthene.	0.40	5	<u>0.54</u>
	Indeno(1.2.3-cd)pyrene	0.20	1	<u>0.27</u>

4.2. Mix design

The designed materials based on sediment are shown in table 6. In order to neutralize the acidity of the materials provided by sediments and to make the treatment to the binders thereafter more effective, all mixtures were treated with 3 % of lime. Following treatment with lime, two rates of hydraulic binders were used to treat the mixtures: 6 and 15% by volume of mix.

The coefficient of curvature (Cc) and uniformity coefficient (Cu) are the best indicators of appreciating the difference between the particle sizes distributions presented above. The value of these parameters can be estimated as follows (eq. 1 and eq. 2)

$$Cu = \frac{D_{60}}{D_{10}} \qquad \text{Eq 1}$$

$$Cc = \frac{D_{30} \cdot D_{30}}{D_{10} \cdot D_{60}} \qquad \text{Eq 2}$$

Note that particle size is said to be uniform if the following two criteria are confirmed (Schlosser, 1988; Holtz and Kovacs, 1991):

- 1<Cc<3: particle size distribution is said to be well graded,

- Cu>6: particle size distribution is said to be well spread.

Table 7 summarises the values of the grading and uniformity coefficients. Uniformity coefficient values are largely higher than the reference value of 6 except for dredged sand which is slightly below. Curve coefficient values are, except for dredged sand, between 1 and 3. This finding means the grading curves for the formulated mixes show good homogeneity (well graded).
Therefore, addition of dredged sands in proportions of 30% appears to fulfil the above-mentioned particle size criteria. According the French guide of road

construction (SETRA-LCPC, 1990), for materials used for backfill layer the organic matter shouldn't exceed 3%. In fact, adding dredging sand decreases the organic matter content in the materials to be below this value.

Tableau 6. Designed materials for recycling sediments and granular addition

| | Mixtures | | Lime (%) | Binders (%) | |
	Sediment (%)	Sand (%)		Cement C1	Cement C2
Raw sed 6C1	100	0	3	6	0
Raw sed 15C1	100	0	3	15	0
Mix 6C1	70	30	3	6	0
Mix 15C1	70	30	3	15	0
Raw sed 6C2	100	0	3	0	6
Raw sed 15C2	100	0	3	0	15
Mix 6C2	70	30	3	0	6
Mix 15C2	70	30	3	0	15

Tableau 7. Grading and uniformity coefficients for the materials

	Raw Sediment	Dredging sand	MIX (30% dredging sand+70% raw sediment)
Cu	11.9	5.2	15.5
Cc	1.2	0.9	1.7

4.3.   Normal Proctor tests and IBI results of treated mixtures

The aim of this investigation is to evaluate the compaction level by following the evolution of dry density and IBI according to the evolution of moisture content of materials. Optimum dry density, moisture content and immediate bearing index (IBI) of all mixtures are given in table 8 and are presented in Fig.6. In the same figure, the saturation degree curves for Sr =80% and Sr =100% are also presented. The dry densities for mixtures treated with C2 vary between [1.52; 1.70] t/m³ which corresponds to water contents range between 14.4 and 20.5. Corresponding bearing Index values are range between [21.0; 29.1]. For mixtures treated with C1, dry densities are between [1.49; 1.66] t/m³, which correspond to water contents range between [17.1; 23.1]. Corresponding CBR Index values are between 19.8 and 26.8. These values are in the same range of the results obtained by Wang et al. (2013), which have studied the stabilization of marine sediments by a lime and a fly ash.

Results presented here show that all the studied formulations respond to the Bearing Index criteria for reuse on embankment layer (IBI min = 20) (LCPC-SETRA, 2000). Nevertheless, mixtures containing dredging sand (30%) and treated with cement C2 give the best characteristics.
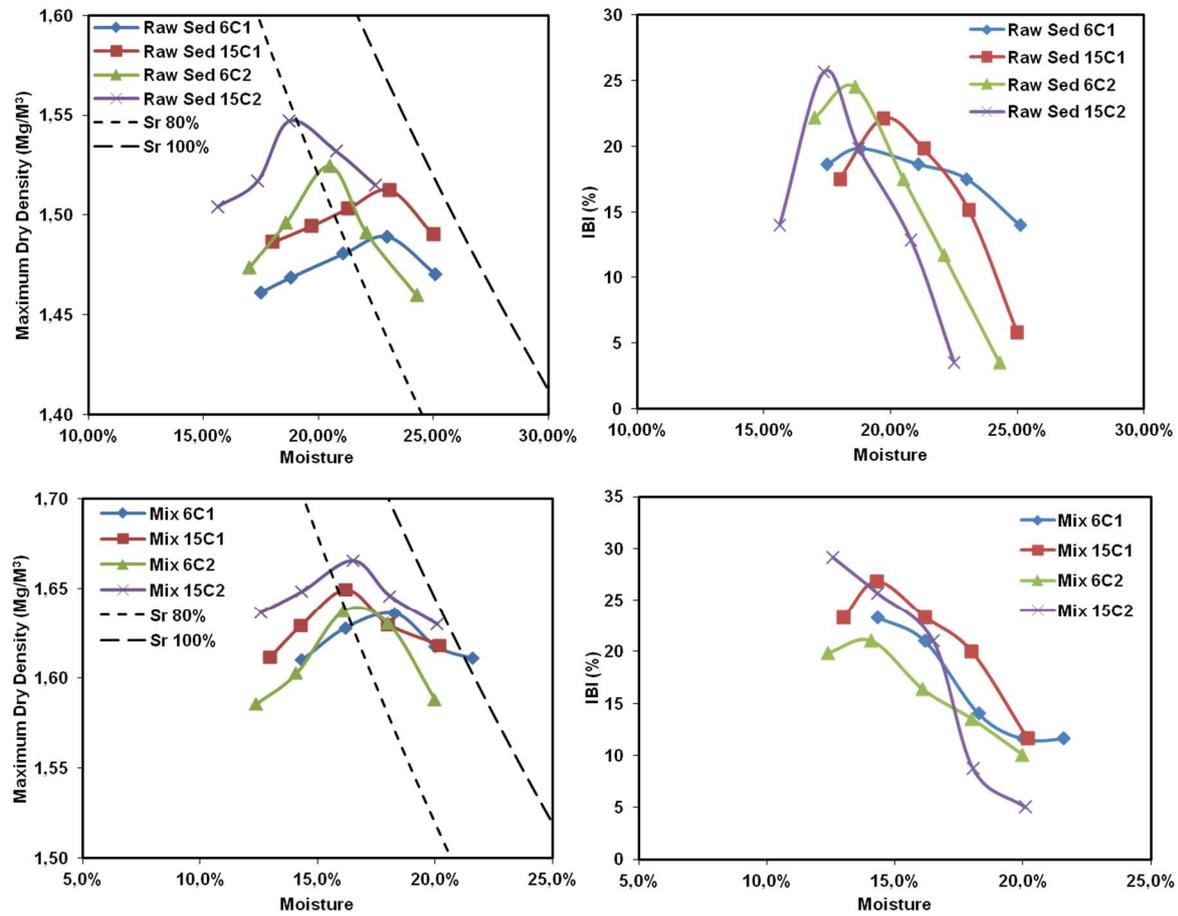

Figure 6. Proctor tests and I CBR of treated mixtures

Tableau 8. Proctor-IPI results for the mixtures treated with cement and quicklime

Mixture	W_{OPN} (%)	ρd_{OPN} (Mg/m^3)	Porosity (%)	IBI
Raw sed 6C1	23.0	1.49	41.93	19.8
Raw sed 12C1	23.1	1.51	41.15	22.1
Mix 6C1	18.3	1.64	36.09	23.3
Mix 12C1	18.0	1.66	35.31	26.8
Raw sed 6C2	20.5	1.52	40.76	24.5
Raw sed 12C2	18.7	1.54	39.98	25.6
Mix 6C2	16.1	1.64	36.09	21.0
Mix 12C2	16.5	1.66	35.31	29.1

4.4. Unconfined compressive strength and indirect tensile strength results

To validate the applicability of mixtures as embankment fill, unconfined compressive strength (UCS) and indirect tensile strength (ITS) are measured at the ages of 7, 28, 60 and 90 days. The Fig.7 shows the results of mechanical strength of testing samples. The UCS and ITS of all mixtures increases upon aging of samples and with the rate of cement treatment. However, the UCS and ITS obtained for mixtures treated with cement C1 are less slightly than those obtained for mixtures treated with cement C2 and mixtures containing dredging sand. It can be seen that the increase of the cement proportion from 6 to 15% in a mixture can improve the strength of the mixture by about 50 % (UCS, ITS).

A value of UCS=1MPa corresponding of the age at which construction site traffic is permitted (LCPC-GTS, 2000) are obtained for all formulations at 28 days of cure, except for mixtures MIX 6C1 and Raw sed 6C1. However, this threshold is reached at 60 days of cure for these two mixtures. For mixtures MIX 15C1 and MIX 15C2 at 60 days of cure. For the mixtures MIX 15C1 and MIX 15C2 at 60 days of cure, the indirect tensile strength is higher than the critical one of 0.25 MPa described in (LCPC-SETRA, 2000), this result indicates that the materials can probably resist to frost.

Results shows the relationship between strength (UCS, ITS) and cement compounds (S+A and Fluxing) of hydraulic road binder used in this study. It can be seen that an increase in the S+A and fluxing from (S+A; Fluxing) = (23.60; 67.96) for cement C1 to (S+A; Fluxing) = (26.19; 69.70) for cement C2 induces an increase in strength (UCS and ITS). That would increase the hydration process of C_3S, C_2S and C_3A, which significantly increase the formation of CSH and porthlandite (Eq.3).

$$2\ C_3S + 6\ H^+ \longrightarrow C_3\ S_2\ H_3 + 3CH \qquad\qquad Eq.\ 3$$

Nevertheless, the presence of organic matter and contaminants in the sediment decreases the compressive and indirect tensile strength for the mixtures. The effect of organic matter on the solidification/stabilization process can be explained from two possible points of view:

From a chemical point of view, organic matter is known for its great water retention capacity, which reduces the quantity of water necessary for the reactions of hydration of the hydraulic binders. In addition, organic matter is composed of humic acid (HA) which reacts with lime present in the hydraulic binders to form the humates calcium (Croisé, 1964; Rekik & al., 2009; Gas'kova, 2013) (equation 4). Therefore, the complexation of the humic acids with calcium cation reduces their available for the reactions of hydration to form CSH and CAH gel.

$$HA\text{-}OH + Ca^{2+} \longrightarrow HA\text{-}OCa^+ + H^+ \qquad\qquad Eq.\ 4$$

From a physical point of view, the presence of organic matter in sediments decreases the specific gravity value of materials and it is accompanied by a decrease in dry density and consequently decreases the strength of mixtures.

These results show that the granular addition can mitigate this effect (Dubois, 2006; Yunus et al., 2011).
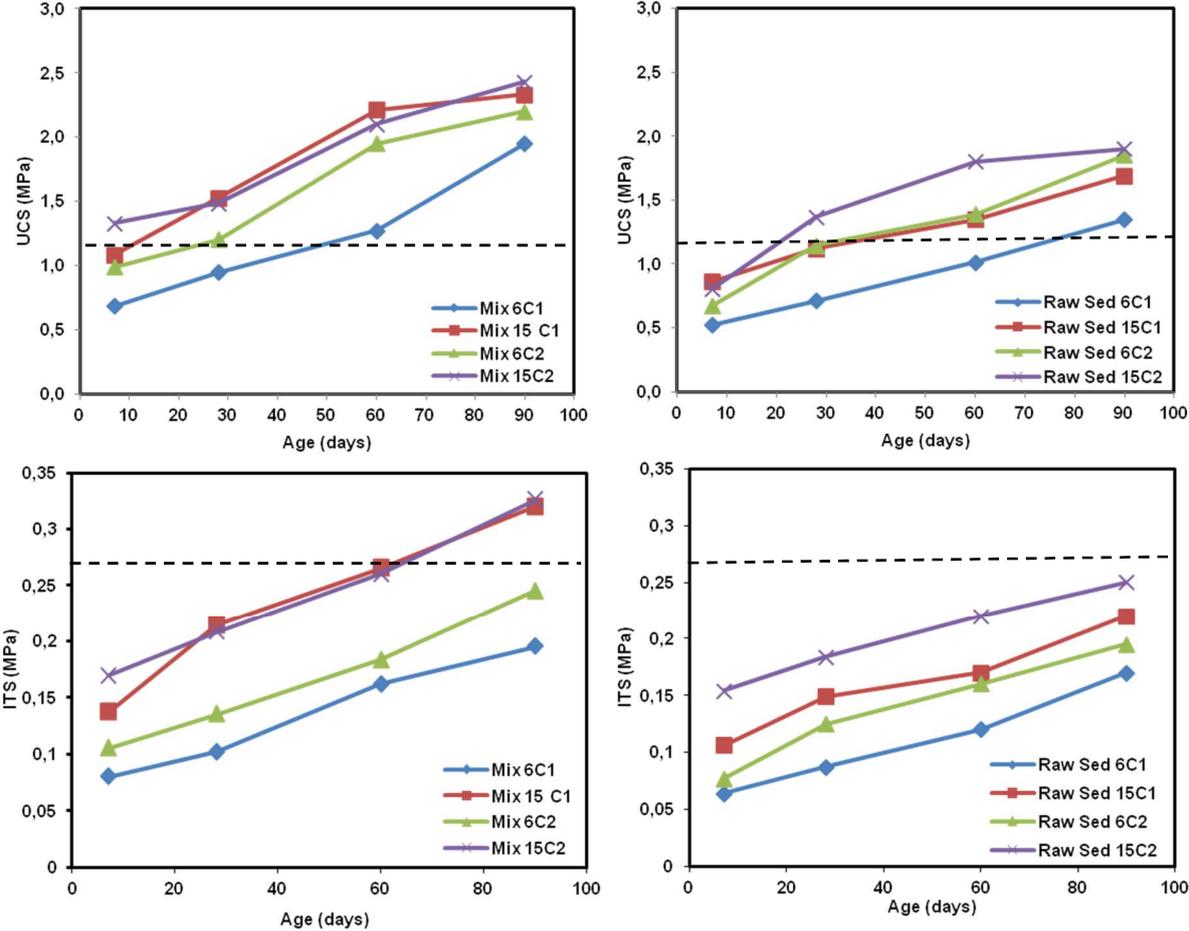

Figure 7. Development of mechanical strength of designed materials

4.5.   Sustainability of designed materials

The results of the measurements of accelerated volumetric swelling (VS), expressed in percentages (%), and indirect tensile strength (ITS) are presented in figures 8. As shown by these results, volumetric swellings of all the mixtures without dredging sand and treated with cement exceed the volumetric swelling limit value of 5%, except the mixtures treated with 6% of cement C2 (VS=4.21). In fact, it was observed that the increase in cement content has not significant effect on the volumetric swelling value. Concerning the mixtures containing dredging sand and treated with cement, only the mixtures treated with cement C2 (6 and 15 % wet) met the acceptance criteria for the volumetric swelling (less than 5%).
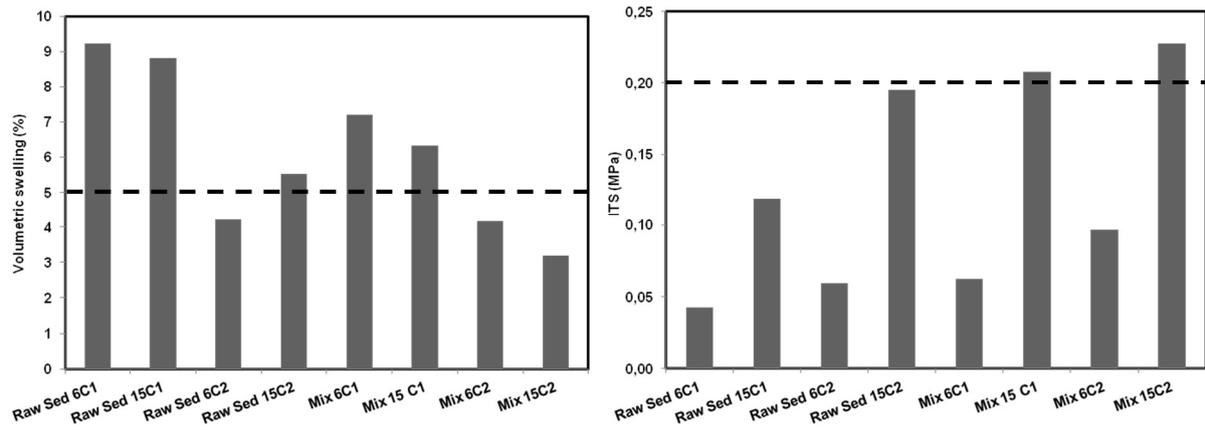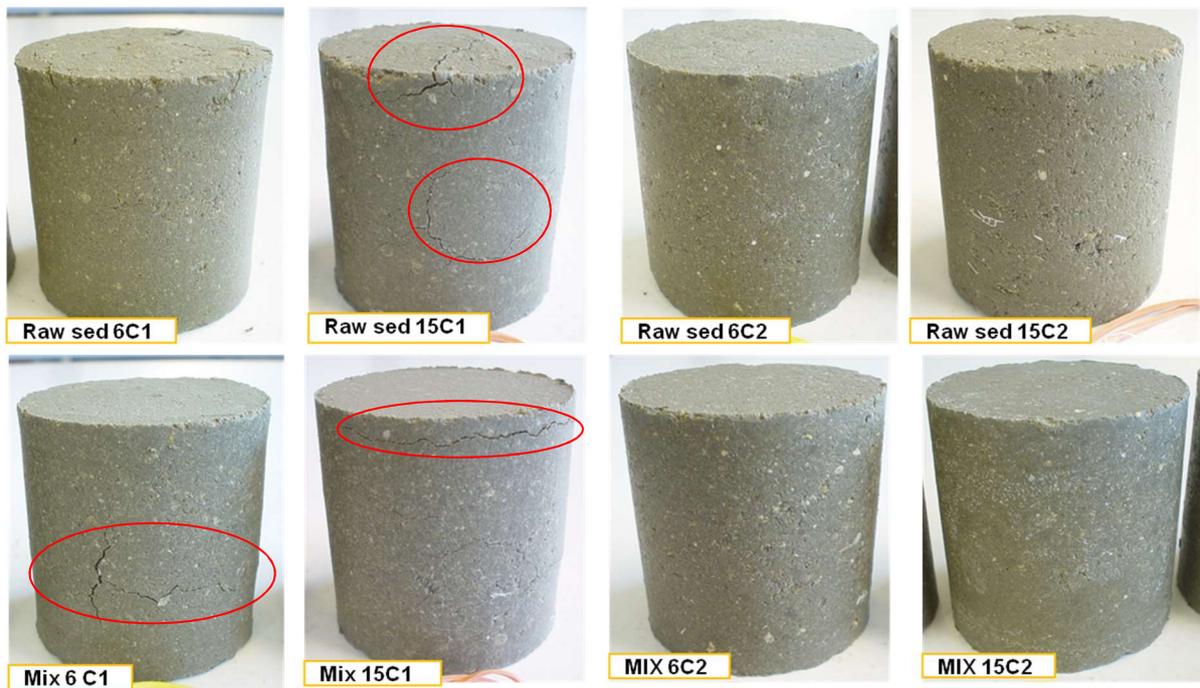
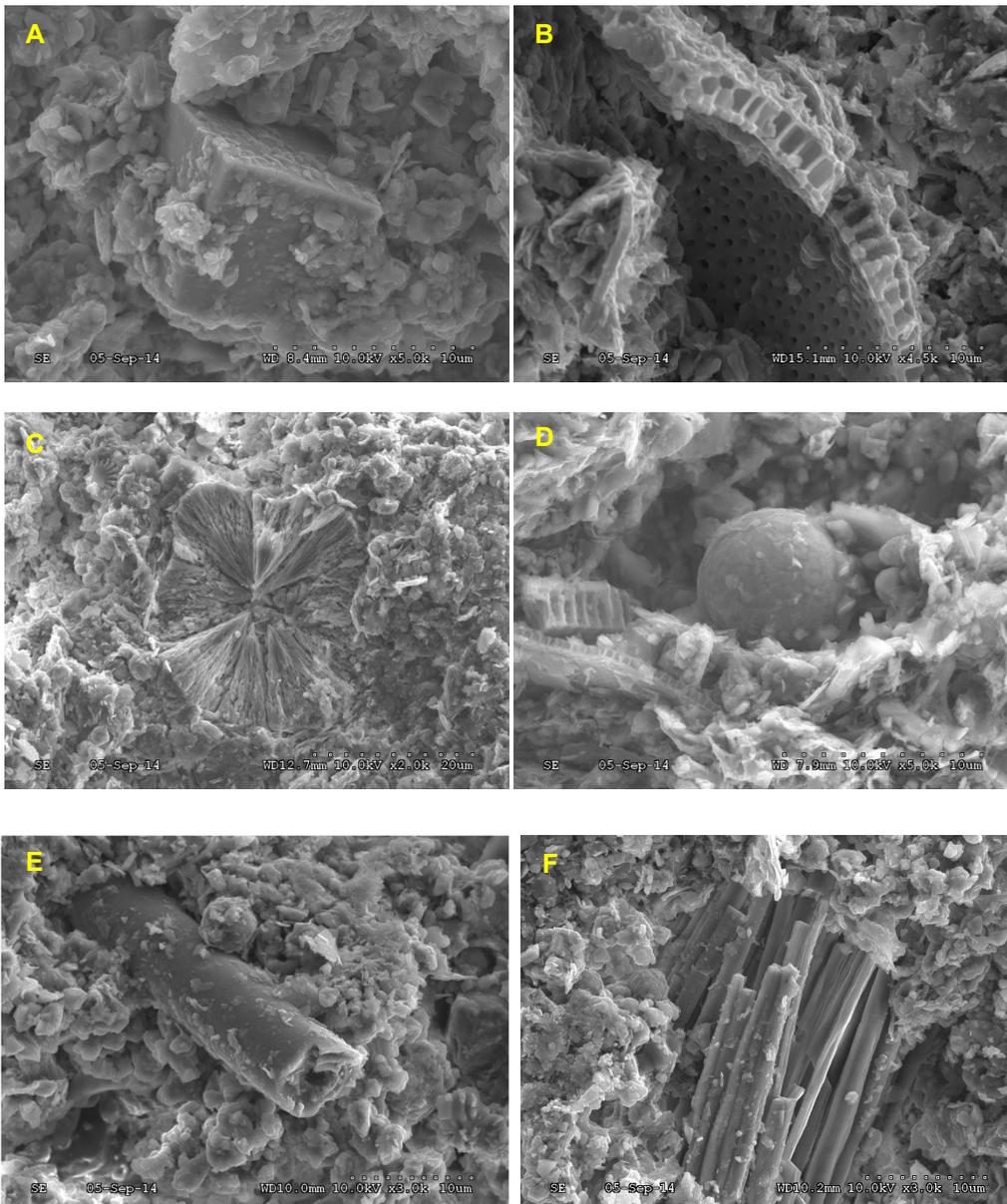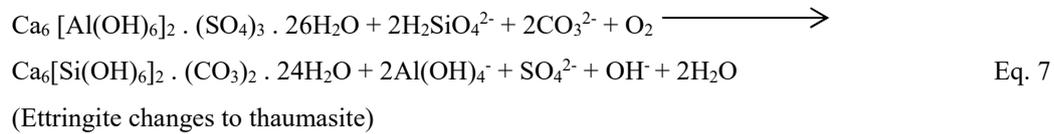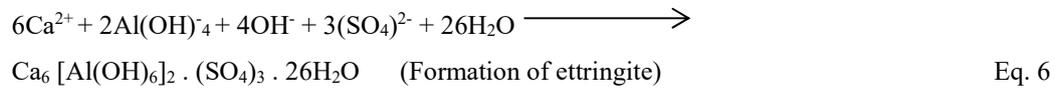Figure 8. ITS and VS of mixture after water aging

Figure 9. Specimens of treated mixtures after water aging

In addition to the influence of the proportion of binders, a second explanation for volumetric swelling could be the reaction between the pyrite (FeS_2), identified in the mineralogical analysis of the dredging sediments (Tab.6) and the ettringite. Swelling resulting from this reaction is reported by many authors (Mitchell and Dermatas, 1992; Rajasekaran, 2002; Rajasekaran, 2005). In fact, the presence of moisture encourages the formation of ettringite and the interaction with the sulphates ($FeSO_4$) present in the sediments forms thaumasite which increases the intra granular porosity. These generate swelling leading to significant cracking in samples (Fig.9). Observations by electron microscopy of the treated samples have

confirmed these analyses (Fig. 10-D-E-F). A simplified geochemical reaction reported by Hunter (1988) for lime induced heave reactions can be summarized as follows:

$$4FeS_2 + 15\ O_2 + 14\ H_2O \longrightarrow 4Fe(OH)_3 + 16H^+ + 8SO_4^{2-} \qquad \text{Eq. 5}$$

$$6Ca^{2+} + 2Al(OH)_4^- + 4OH^- + 3(SO_4)^{2-} + 26H_2O \longrightarrow$$

$$Ca_6\ [Al(OH)_6]_2\ .\ (SO_4)_3\ .\ 26H_2O \qquad \text{(Formation of ettringite)} \qquad \text{Eq. 6}$$

$$Ca_6\ [Al(OH)_6]_2\ .\ (SO_4)_3\ .\ 26H_2O + 2H_2SiO_4^{2-} + 2CO_3^{2-} + O_2 \longrightarrow$$

$$Ca_6[Si(OH)_6]_2\ .\ (CO_3)_2\ .\ 24H_2O + 2Al(OH)_4^- + SO_4^{2-} + OH^- + 2H_2O \qquad \text{Eq. 7}$$
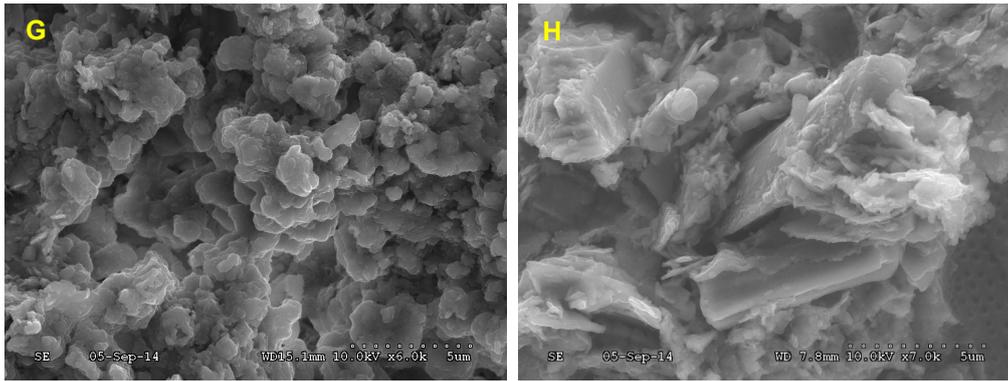
(Ettringite changes to thaumasite)

Figure 10. SEM micrographs of the designed materials based on dredged marine sediment: A) halite; B) seashell; C) radiating aragonite crystals; D) framboidal pyrite FeS_2; E) organic matter; F) thaumasite; G) void; H) pothlandite

The relation between the porosity and the volumetric swelling is presented in figure 11 using linear regression analysis. These results suggested that the porous structure was a significant determining factor to be evaluated and optimized for assuring satisfactory sustainability of designed materials. Therefore, it was of primary importance to incorporate an appropriate amount of the selected aggregates materials for providing an optimum particle size distribution.

The values of porosity are estimated from the value of maximum dry density (ρ_d) using a specific formula, as presented in the following:

$$n = 1 - \frac{\rho_d}{\rho_s} \qquad \text{Eq. 8}$$

Where ρ_d is the dry density and ρ_s is the specific density of mixture.

From the correlation it is clear that the volumetric swelling of mixtures mainly depends on the porosity. However, due to their porous structure, the presence of seashells in the sediments also generates an increase in the porosity of designed materials.

Consequently, this high porosity increases the exposed surface of the material to water and leads to chemical interaction of the chemical residues (Fe_2S, ettringite, humic and fulvic acid) presenting in mixtures.

Volumetric swelling was also accelerated by the cure conditions, which were done in water at a temperature of 40°C and in an alkalinity that originated from binders treatment. Furthermore, an increase in porosity decreases the density of mixtures and leads to a reduction of the indirect tensile strength.
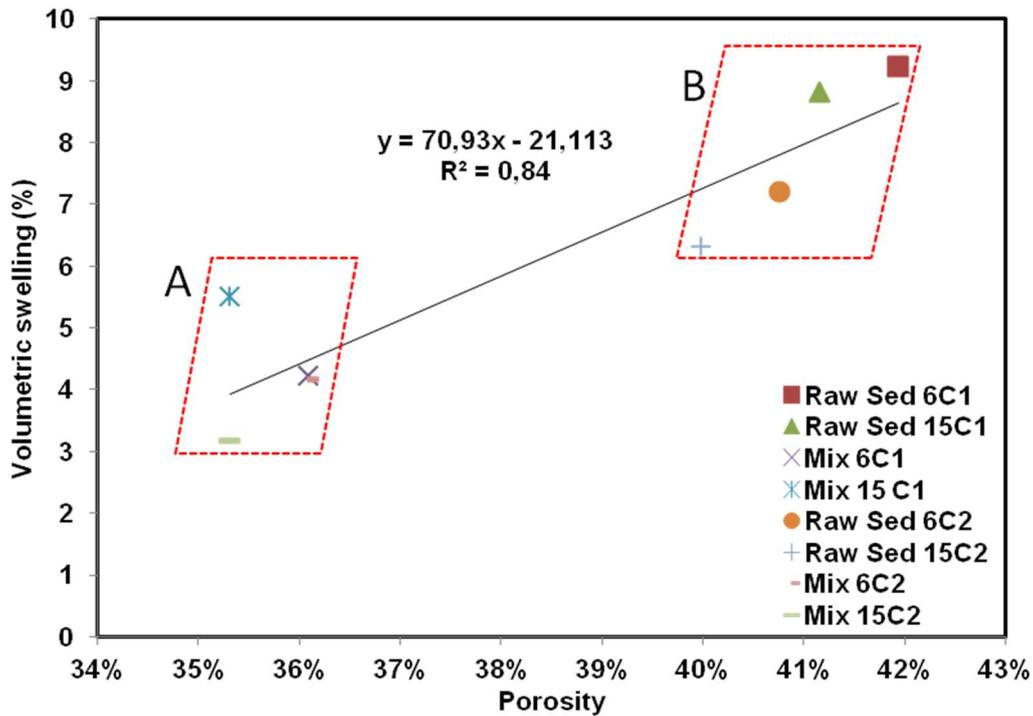
Note A: treated mixtures (sediment-dredging sand); B: treated raw sediment

Figure 11. Relationship between porosity and VS of treated mixtures

The treatment suitability results are shown in figure 12. According the criteria for suitability of treatment (LCPC-SETRA, 2000), the mixture containing dredging sand (30%) and treated with 12% of cement C2 is the only one to meet the criteria for suitable treatment. Mix 15C1, Raw Sed 15C1 and Raw Sed 15C2 are doubtful for treatment with hydraulic road binder. Use of these mixtures in road construction applications depends on the construction site context and the potential to bring about improvements by increasing the spread rate for example.
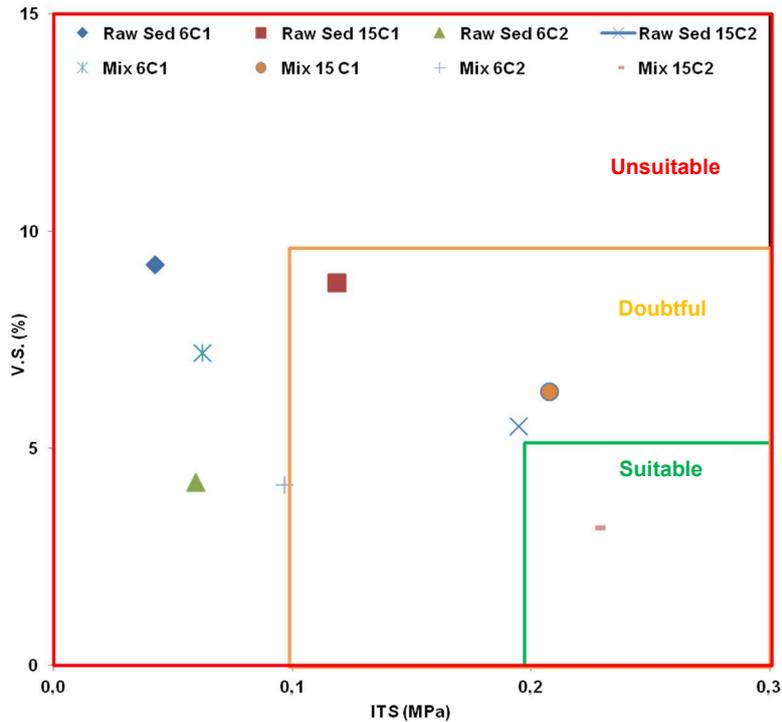
Figure 12. Correlation between ITS and VS of treated mixtures measured after sustainability tests

4.6. Road materials classifications

For materials treated with hydraulic road binder, the estimated values at 360 days are calculated from measured values of tensile strength value TS and Young's modulus E at 28 days (NF EN 14227-3, 2004). Figure shows the limits for different materials classes, as defined by test standard NF P98-114-3 (2009).

$$TS_{28}=0,8 \times ITS_{28} \qquad \text{Eq. 9}$$

$$TS_{360}=TS_{28}/0.60 \qquad \text{Eq. 10}$$

$$E_{360}=E_{28}/0.65 \qquad \text{Eq. 11}$$

From these results, it is interesting to note the beneficial impacts of the granular addition and increases in hydraulic binder percentage in the mixtures designed. The addition of 30% of sand reduces the porosity of the materials and reduces the effect of impurity elements such as organic matter and sulphates. Increasing cement content allows the formation of additional hydration product (CSH, CAH) which contributes to the solidification/stabilization of treated materials. Despite the mixtures Mix 15C2 and Mix 15C1 are same classified according to the chart of the Fig.13. In contrast, the results of suitable tests to treatment with hydraulic binders have shown previously, that the only mixture Mix 15C2 that met the tests criteria for use as embankment materials.
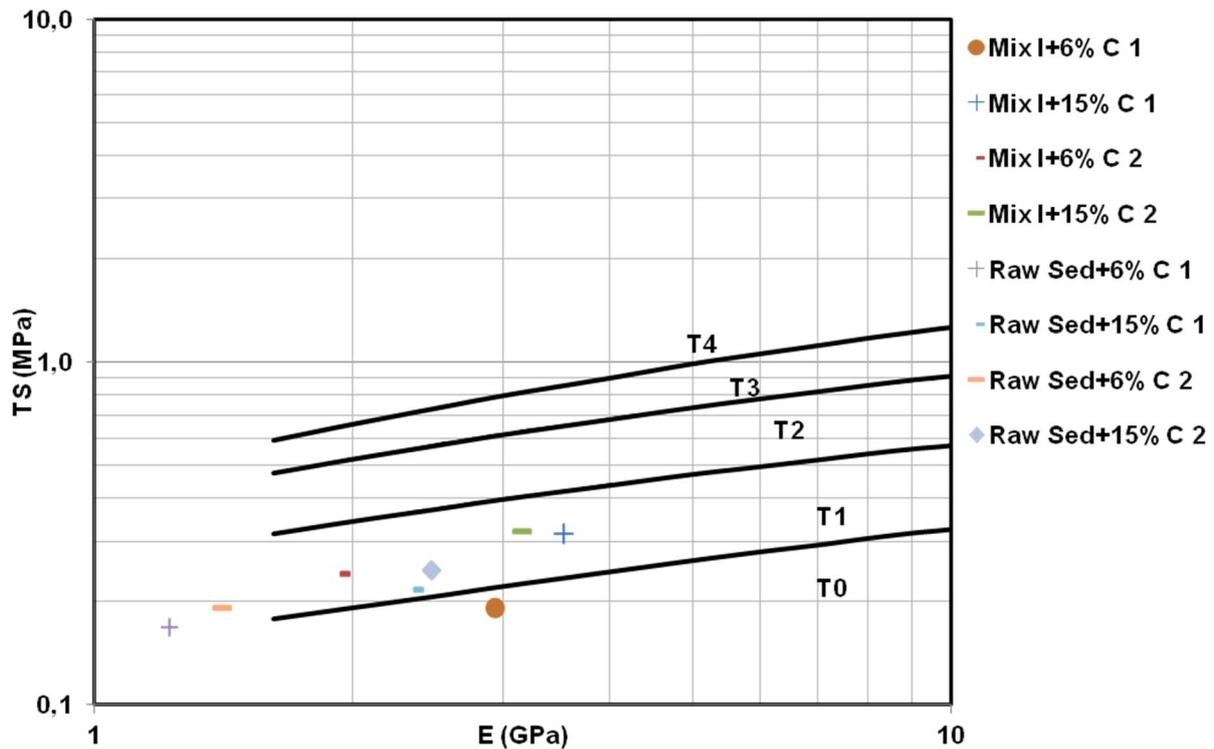
Figure 13. Treated materials according the GTS (SETRA-GTS, 2000)

5. Conclusion and perspective

The sustainable management of marine dredged sediments represents a major challenge in the development of circular economy in the road construction sector and the conservation of natural resources. The literature studies on this field were focused on finding the optimum packing density using granular corrector (sand, slag, fly ash...) regardless interactions that may exist between hydraulic binders and chemical compounds present in the dredged sediments (Pyrite, organic matter). This involved a limited use of large quantities of dredged sediment produced annually.

The main objective of this study was to identify the essential parameters for designed road materials based on the large fraction of contaminated sediments. Results obtained highlight a potential for the use of treated mixtures containing dredged marine sediments and sand in sub layer-road construction. From this study, we can conclude that:

- Adding granular addition for sediments leads to an increased packing density and decrease the porosity. In addition, it decreases the concentration of contaminants and organic matter in designed materials. This can have a significant influence in the exchange process between treated materials and their environment,

- The durability testing presented in this study are essential to assess the stability of the formulated material face a real and frequent risk during the life of a road, which is the rise of groundwater to the subgrade,

- The treatment of the mixtures with 15% of hydraulic road binders based on high content of fluxing and glass forming oxides increases the mechanical performances, and improve the durability of mixtures,

- The presence of sulfates in the sediment increases the risk of swelling due to their reaction with ettringite compounds. For this purpose, a solution to prevent this risk is to use an adequate hydraulic binders that contains the least aluminates,

A large scale experimental road was making to monitor the environmental impact of the use of contaminated dredged sediment in embankment layer. The formulation selected for the realization of the test road is the Mix12C2 formulation which contains, in volume ratio 30 % sand and 70% sediment, treated with 3 % lime and 15 % binder C2. The size of this experimental scale is: Long 10 m and wide = 5 m, with a height of 30 cm. The first chemical results from percolating water show that there is no release of contaminants exceeding the thresholds of hazardous waste. The results of mechanical tests, in situ and laboratory showed good strength to meet the requirements of the scope statement for realization of road under layers (GTS 2000) (for more detail see www.SETARMS.org)

Platform preparation

Drain system

Raw sediments + sand

Mix treatment with lime

mix treatment with cement

Mix compaction

References

ALI, I. B. H., LAFHAJ, Z., BOUASSIDA, M., & SAID, I. (2014). Characterization of Tunisian marine sediments in Rades and Gabes harbors. International Journal of Sediment Research, 3, 009.

Boutouil, M., & Saussaye, L. (2011). Influence of granulometric corrector on the properties of the sediments treated with hydraulic binders. EUROPEAN JOURNAL OF ENVIRONMENTAL AND CIVIL ENGINEERING, 15(2), 229-238.

Chavel, A., Nobrega, M.T., Tessier, D. (1985). The effect off compaction and addition one LATESOL. Soil Microrphologie. vol. 1. pp. 10-18.

Colin, D. (2003). Valorisation de sédiments fins de dragage en technique routière. Doctoral dissertation, Caen.

Croisé, R. (1964). Traitement des sols aux liants hydrauliques. École nationale du génie rural, des eaux et des forêts, Nancy (France).

Diana, L.D., Limaa, Sérgio M. Santosa, Heinrich, W. Schererb, Rudolf J. Schneiderc, Armando C. Duartea, Eduarda B.H. Santosa, Valdemar I. Estevesa (2009). Effects of organic and inorganic amendments on soil organic matter properties. Geoderma, Volume 150, Issues 1–2, pp. 38–45

Dubois, V., Abriak, N. E., Zentar, R., & Ballivy, G. (2009). The use of marine sediments as a pavement base material. Waste Management, 29(2), 774-782.

Etat des lieux du dragage en Manche (WP1). (2015). Association des Ports Locaux de la Manche (en ligne). http://www.setarms.org.

NF EN 13286-2. (2005). Unbound and hydraulically bound mixtures. Test methods for the determination of the laboratory reference density and water content. Proctor compaction. European Committee for standardization.

NF EN 13286-42. (2003). Unbound and hydraulically bound mixtures. Test method for the determination of the indirect tensile strength of hydraulically bound mixtures. European Committee for standardization.

NF EN 13286-47. (2003). Unbound and hydraulically bound mixtures. Test method for the determination of California bearing ratio, immediate bearing index and linear swelling. European Committee for standardization.

Gas'kova, O. L. et Sklyarova, O. A. (2013). Influence of natural organic acids on the Mg/Ca ratio in the bottom sediments of highly mineralized lakes. Russian Geology and Geophysics, vol. 54, no 6, p. 637-645.

Hake, D. (2003). Valorization of fine sediments of dredging in road engineering.Thesis of doctorate. University of Caen. 180 p.

Hunter, D. (1988). Lime-induced heave in sulfate-bearing clay soils. Journal of geotechnical engineering, 114(2), 150-167.

JOCE, 1975. Council Directive of 15 July 1975 on waste. Reference: 75/442/EEC. Official Journal of European Communities No. L194, 25.7.1975, p. 39.

JOCE, 2003. Council Derective of 19 December 2002. Reference: 2003/33/EC. Official Journal of European Communities No. L11, 16.1.2003, pp. 27–49.

LCPC-SETRA. (1992). Construction of the embankments and the subgrades - Technical Guide, Booklets I and II. 204 p.

LCPC-SETRA. (2000). Soil stabilization to limes and/or hydraulic binders. Application to the realization of the embankments and sub grades - Technical Guide. 240 p.

Maherzi, W., Ben Abdelghani, F., Boutouil, M., Saussaye, L. (2011). Sustainable Environmental Treatment and Reuse off Dredged Marine Sediments in Road Construction. ISWA 2011.17- October 20th. 2011. Daegu. Korea. PP 456-466.

Maherzi, W., & Abdelghani, F. B. (2014). Dredged Marine Sediments Geotechnical Characterisation for Their Reuse in Road Construction. Engineering Journal, 18(4), 27-37.

Miraoui, M., Zentar, R., & Abriak, N. E. (2012). Road material basis in dredged sediment and basic oxygen furnace steel slag. Construction and Building Materials, 30, 309-319.

Mitchell, J. K., & Dermatas, D. (1992). Clay soil heave caused by lime-sulfate reactions. Innovations and uses for lime, (1135), 41.

Ohfuji, H. and Rickard, D. (2005). Experimental synthesis of framboids – a review, Earth Science Reviews, 71, 147-170.

Pavoine, A., Brunetaud, X., & Divet, L. (2012). The impact of cement parameters on Delayed Ettringite Formation. Cement and Concrete Composites, 34(4), 521-528.

Pirrie, D., Rollinson, G.K. (2011). Unlocking the applications of automated mineral analysis. Geology Today. 27(6). 235-244.

Rajasekaran, G., & Rao, S. N. (2002). Compressibility behaviour of lime-treated marine clay. Ocean engineering, 29(5), 545-559.

Rajasekaran, G. (2005). Sulphate attack and ettringite formation in the lime and cement stabilized marine clays. Ocean Engineering, 32(8), 1133-1159.

Rayssac, E., Auriol, J. C., Deneele, D., De Larrard, F., Ledee, V., & Platret, G. (2009). Valorisation de laitiers d'aciérie LD pour les infrastructures routières. Bulletin des laboratoires des ponts et chaussées, (275), pp-27.

Rekik, B., & Boutouil, M. (2009). Geotechnical properties of dredged marine sediments treated at high water/cement ratio. Geo-Marine Letters, 29(3), 171-179.

Rollinson, G., Andersen, J.C.Ø., Stickland, R.J., Boni, M., and Fairhurst, R., 2011., Characterization of non-sulphide zinc deposits using QEMSCAN®: Mineral Engineering, v. 24, p. 778–787.

Sannier, L., Levacher, D., Jourdan, Mr. (2008). Economic discrimination of methods of treatments of contaminated marine sediments treated using hydraulic binders.National days Coastal Genius - Civil engineering. Sophia-Antipolis. p 821-830.

Siham, K., Fabrice, B., Edine, A. N., & Patrick, D. (2008). Marine dredged sediments as new materials resource for road construction. Waste management, 28(5), 919-928.

Silitonga, E., Levacher, D., & Mezazigh, S. (2009). Effects of the use of fly ash as a binder on the mechanical behaviour of treated dredged sediments. Environmental technology, 30(8), 799-807.

Silitonga, E., Levacher, D., & Mezazigh, S. (2010). Utilization of fly ash for stabilization of marine dredged sediments. European Journal of Environmental and Civil Engineering, 14(2), 253-265.

Wang, D. (2011). Solidification and valorization of the sediments of the wearing of Dunkirk in road work. Thesis of doctorate. Ecole Nationale Supérieure of the Mines of Douai. 156 p.

Wang, D. X., Abriak, N. E., Zentar, R., & Xu, W. (2012). Solidification/stabilization of dredged marine sediments for road construction. Environmental technology, 33(1), 95-101.

Yan, D. Y., Tang, I. Y., & Lo, I. M. (2014). Development of controlled low-strength material derived from beneficial reuse of bottom ash and sediment for green construction. Construction and Building Materials, 64, 201-207.

Yallop, M. L., de Winder, B., Paterson, D. M., & Stal, L. J. (1994). Comparative structure, primary production and biogenic stabilization of cohesive and non-cohesive marine sediments inhabited by microphytobenthos. Estuarine, Coastal and Shelf Science, 39(6), 565-582.

Yunus, N. M., Wanatowski, D., & Stace, L. R. (2011). Effect of Humic Acid on Physical and Engineering Properties of Lime-Treated Organic Clay. Engineering and Technology, 59 (201), 1.

Van Veen, E., Andersen, J.C., Rollinson, G.K., Coggan J.S.. (2013) Characterisation of dredged harbour sediment using automated mineralogy, GESeD: Gestion Environementale des Sediments de Dragage, Caen, France, 10th - 12th Apr 2013.

Zentar, R., Dubois, V., & Abriak, N. E. (2008). Mechanical behaviour and environmental impacts of a test road built with marine dredged sediments. Resources, Conservation and recycling, 52(6), 947-954.

Zentar, R., Wang, D., Abriak, N. E., Benzerzour, M., & Chen, W. (2012). Utilization of siliceous–aluminous fly ash and cement for solidification of marine sediments. Construction and Building Materials, 35, 856-863.

Zri A., Abriak N.E., Zentar R. (2011). Caractérisation physico-mécanique d'un sédiment brut et traité à la chaux. EJECE. Vol. 15. n° 2/2011, pp. 239-267