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The use of marine sediments as a pavement base material

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ABSTRACT

The management of marine sediments after dredging has become increasingly complex. In the context of sustainable development, traditional solutions such as immersion will be increasingly regulated. More than ever, with the shortage of aggregates from quarries, dredged material could constitute a new source of materials.

In this study of the potential of using dredged marine sediments in road construction, the first objective is to determine the physical and mechanical characteristics of fine sediments dredged from a harbour in the north of France. The impacts of these materials on the environment are also explored. In the second stage, the characteristics of the fine sediment are enhanced for use as a road material. At this stage, the treatment used is compatible with industrial constraints. To decrease the water content of the fine sediments, natural decantation is employed; in addition, dredged sand is added to enhance the granular distribution and to reinforce the granular skeleton. Finally, the characteristics of the mix are enhanced by incorporating binders (cement and/or lime). The mechanical characteristics measured on the mixes are compatible with their use as a base course material. Moreover, the obtained results demonstrate the effectiveness of lime in the mixes. In terms of environmental impacts, on the basis of leaching tests and according to available thresholds developed for the use of municipal solid waste incineration (MSWI) bottom ash in road construction, the designed dredged mixes satisfy the prescribed thresholds.

1. Introduction

Dredging operations are necessary to maintain navigation in waterways and access to harbours. Each year, several 100 millions of tons of materials are dredged around the world (Boutin, 1999). These materials, ranging from rocks to clays, can contain a variable amount of organic matter and different types and levels of contaminants.

Management of dredged sediments is a worldwide problem. After dredging, traditional solutions such as dumping the sediments at sea are constrained by national and international regulations. Alternative solutions, such as terrestrial disposal, are costly and require large areas (LIFE, 2002; Grégoire, 2004). The development of beneficial use strategies for dredged sediments is therefore necessary.

According to European directive number 75/442/CE (JOCE, 1975), dredged sediments are classified as waste under section 17 05 05* (polluted sediments) and section 17 05 06 (other sediments). Due to shortages of natural resources and the sustainable development approach adopted by several countries, the beneficial use of dredged sediments has gained broad acceptance in different domains such as civil engineering, agriculture, and manufacturing (Centre Saint Laurent, 1993; Boutouil, 1998; LIFE, 2002; Ulbricht, 2002; Colin, 2003). The beneficial use in the civil engineering domain, which consumes over 400 million tons of such materials each year in France (Michel, 1997; UNPG, 2005), is interesting from several points of view. With environmental constraints concerning the opening of new quarries, combined with the continuous increase in demand for aggregates, dredged sediments can be viewed as a new source of materials. In the road construction field, the characteristics of dredged materials could be similar to those of currently used materials, from grain size distribution (fine to coarse aggregates) to the variability of required mechanical performances for the road layers.

Previous research on the use of raw fine sediments in road construction has shown that treatment by hydraulic binders could satisfy the needed mechanical characteristics. However, the proportion of hydraulic binders needed to meet prescribed specifications is important. For sediments from Le Havre Harbour (France), about 15% of a hydraulic binder was necessary (Boutouil, 1998). The need for a large amount of hydraulic binder makes the use of raw dredged sediments unlikely from an economic point of view. Moreover, the presence of organic matters can constitute a problem with regards to cement hydration (Kujala et al., 1996). According to Clare and Sherwood (1954), different types of organic matter can interact

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differently with cement. A decrease in strength can be found, but this is not systematic. The presence of acid compounds, such as fulvic acids, can slow the rise of pH, preventing the pozzolanic reactions. In addition, during the hydration phase of cement, organo-mineral complex, which is often found in organic soils, breaks up with increasing pH, releasing organic matter. This organic matter can fix the released calcium ions, which cannot participate in the formation of hydrates. The addition of lime to supply the organic matter with calcium ions and to allow for normal cement hydration may be an interesting solution.

In this context, this study is aimed at developing a road construction material based on fine dredged sediments in combination with sand and binders. To evaluate the influence of binders on the mechanical behaviour of the designed materials, mixes are treated with cement and with a combination of cement and lime, and compared. Moreover, the environmental impacts of the raw fine sediments and the designed mixes are investigated by performing leaching tests.

2. Materials and methods

After description of the site from where the sediments are dredged, the basic characteristics of the studied materials are discussed and a developed methodology is implemented to identify mixes for use in the road construction field.

2.1. Site description

The marine sediments used in this study were dredged from Dunkirk Harbour (Fig. 1). This harbour, situated in the north of France, is well known for its intensive industrial activities (e.g. petroleum, gas, and steel). Dredging operations to maintain waterways generate over 3.5 M m^3 of dredged sediments each year (IFREMER and MATE, 1999). The dredged fine sediments presented in this study are from the West Harbour (Lambert coordinates: $X = 588200$, $Y = 370600$). These sediments are denoted D1 material. Previous studies have shown, according to French legislation (JO, 2000), that the level of pollution in the sampling zone is low, and that the dredged material is mainly composed of silt (Grégoire, 2004; Mac Farlane, 2004). The sediments are dredged from the sea-bed at about 23 m in depth. Samples of the dredged materials were stored in hermetic containers of 0.054 m^3 in volume.

2.2. Characterization of dredged sediments

2.2.1. Environmental impact of fine raw sediments

In order to characterize the environmental impacts of the dredged sediments (D1 material), leaching tests were performed on three samples from the same batch according to European test standard EN 12457-2 (AFNOR, 2002). In the leaching tests, a liquid-to-solid ratio of ten was adopted. In the leachates, metallic elements and ions as fluorides, chlorides and sulphates were analyzed, whereas BTX, hydrocarbons, and PAH were analyzed on the solid matrix.

The average values from the three tests are shown in Table 1. According to the prescribed limits establishing the criteria and procedures for the acceptance of waste at landfills (JOCE, 2003), the disposal of the material on a terrestrial site would require treatment due to the high levels of chlorides. For the reuse of dredged sediments in road construction, at present, no specific threshold has been developed. However, according to French order No. 94-IV-1 of May 1994 regarding the beneficial use MSWI bottom ash (FME, 1994), the dredged sediments could be allowed for use in road construction.

Table 1
Analysis of physico-chemical elements in leachate after leaching test

Tests	After leaching test
Soluble fraction (mg/kg)	«17,780»
pH	[8]
As (mg/kg)	[<0.5]
Cd (mg/kg)	[<0.1]
Cr (mg/kg)	[<0.1]
Cr(VI) (mg/kg)	[<0.1]
Cu (mg/kg)	[<0.5]
Hg (mg/kg)	[<0.01]
Ni (mg/kg)	[<0.4]
Pb (mg/kg)	[<1]
Zn (mg/kg)	[<0.5]
Cyanide (mg/kg)	[<0.1]
Fluorides (mg/kg)	[7.8]
Chlorides (mg/kg)	▹32,700◃
Sulphates (mg/kg)	«3100»
Ammonium (mg/kg)	[200]
Phenol index (mg/kg)	[<0.1]
TOC (mg/kg)	[250]
Tests	On solid matrix
COT (mg/kg)	[26,000]
Benzen–Toluene (mg/kg)	[<5]
Ethylbenzen–Xylen (mg/kg)	[<10]
PCB (seven elements) (mg/kg)	[<0.01]
Hydrocarbon (mg/kg)	[13]
HAP (mg/kg)	[0.806]

References	Pollution level					
European directive 2003/33/CE (JOCE, 2003)	Low	Class III Inert waste	Class II Non-dangerous waste	Class I Dangerous waste	Treatment to store	High
		[ ]	« »	§§	▹◃	

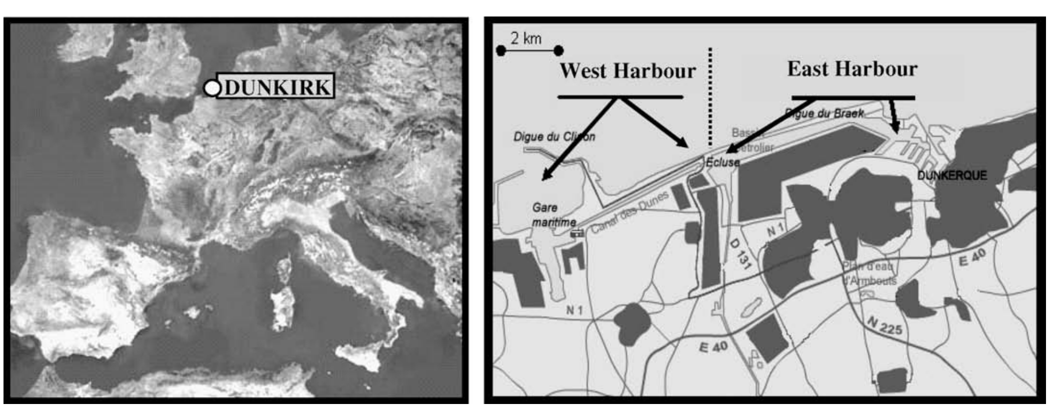

Fig. 1. Location of Dunkirk (left) and Dunkirk Harbour (right).

2.2.2. Physical characteristics

The main physical characteristics measured in the dredged sediments are reported in Table 2. Using oven drying at 60 °C, the measured initial water content is about 156%. This high water content is typical of dredged sediments and depends mainly on the type of sediments, but also on the type of equipment used for dredging. The grain size distribution, obtained using the laser diffraction technique, confirmed that the sediments are composed mainly of silt. The fine sand proportion is about 37% and the clay fraction is about 5%. The clay fraction activity, measured by the methylene blue test, is low. In contrast, the measured consistency limits seem to be abnormally high for a silty material. The liquid limit (w_L) of the sediments, which represents the limit between the liquid state and the plastic state as measured by the percussion-cup method, is about 97%, and the plastic limit (w_P), which represents the limit between the plastic state and the solid state as measured by the rolling test method, is about 45%. According to the plasticity index (*I*p), defined as the difference between the liquid and the plastic limits, the sediments exhibit similar characteristics as very cohesive clays with a very low permeability (SETRA, 1992). The specific gravity, measured with a helium pycnometer, is about 2530 kg/m^3. This value is lower than values adopted for standard materials (2650 kg/m^3), and is due to the high amount of organic matter in the sediments.

The quantity of organic matter contained in the sediments was measured by the ignition method, according to French test standard XP P 94 047 (AFNOR, 1998b), and by the chemical method according to test standard NF ISO 14235 (AFNOR, 1998a). In the first method, the samples were burned for 6 h at 450 °C. The measured organic matter content was about 7.1%. In the second method, the organic matter content, calculated by multiplying the measured organic carbon content by 1.72 (Mustin, 1987), was about 4.5%. According to these results, the dredged sediments can be considered as moderately organic. However, specific studies on the effects of organic matter content on the consistency limits of dredged sediments has revealed a significant effect on the plasticity index (Zentar et al., 2005).

2.3. Methodology for re-use

The preliminary study performed on fine dredged sediments (D1) revealed high initial water content, high plasticity of the material, and a moderate amount of organic matter. According to the Unified Soil Classification System (USCS) and to the guide in use in France (SETRA, 1992), the studied sediments correspond to OH class material and to F-A4 class material, respectively. This type of material is difficult to use in road construction due to its sensitivity to water content and its compressibility. Moreover, a complementary study performed on the material revealed a low bearing capacity ratio.

To enhance the characteristics of the fine dredged sediments to suit the prescribed performance for use as road construction materials, a methodology was implemented which consists of: (1) decreasing the water content of the sediments, and (2) increasing its mechanical performance.

The difficulties with decreasing the water content of fine dredged sediments have been described by several authors (Migniot, 1989; Dubois, 2006). In this study, natural decantation is first considered as a method to reduce the initial water content of the sediments. To explore the efficiency of this method, a 15 cm thick sediment layer was placed on top of a draining layer. After three weeks to one month at room temperature, the average decrease in water content ranged between 60% and 80%. At the beginning of the dewatering process, the decrease in water content is mainly controlled by the consolidation under the sediment's self-weight. At this stage, the dissolved salts in the pore water are evacuated. At the end of this dewatering stage, the water content decrease is mainly controlled by evaporation. To accelerate the process of evaporation, the sediments were placed in an air-drying oven at 40 °C, which represents summer site conditions. Depending on the thickness of the sediment layer (15–20 cm in this study), the water content decreased after 2–3 days to about 40%. To increase the rate of water content decrease, industrial solutions such as physical or thermal treatments could also be considered. However, these solutions are costly and are of variable efficiency.

To improve the sediment stiffness, dry inorganic sandy material was added to enhance the grain size distribution. By adding selected dry granular material, the water content and organic matter content are decreased artificially and the granular skeleton is improved at the same time. In this study, dredged sand from Dunkirk Harbour, referred to as SD material, was used. The use of this material offers several advantages. First, the availability of the material at the same site makes it easier to perform the mixing. It also offers an alternative solution for the management of dredged sand to the harbour managers. Previous studies on the performance of dredged sand as road construction material have revealed a very low bearing capacity ratio. Sand performance has been improved by adding sand from quarries in order to meet the specifications of usable materials in sub-base layers (Abriak et al., 2003; Abriak and Grégoire, 2003).

The methodology adopted to optimize the mix of fine dredged sediment and dry dredged sand was based on one hand on the water content decrease induced by the dry sand, and on the other hand by improving the grain size distribution of the mix. To ensure a well-graded mix, the coefficients of uniformity and the coefficient of curvature, defined in Eqs. (1) and (2), are considered. For a sandy mix, to ensure a well-graded material, the coefficient of curvature must be between 1 and 3, and the coefficient of uniformity must be greater than 6, according to the USCS classification (Holtz and Kovacs, 1991)

$$\mathrm{Cu} = \frac{D_{60}}{D_{10}} \tag{1}$$

$$\mathrm{Cc} = \frac{D_{30}^2}{D_{10} \times D_{60}} \tag{2}$$

where D_x is the grain diameter, in mm, for which *x*% of the sample are finer.

A classic cement type with rapid setting and a resistance to sulphate attack, denoted CEM I 42.5R HSR LA, is used to form a material resistant to traffic and climatic stresses. The used cement proportion is fixed at 6% of dry mass of the mix, which is the typical amount used in the field of road construction. This component, considered a fine additive, is used into the study of optimisation of the grain size distribution and the determination of Cu and Cc.

To overcome the problem of cement hydration, improve the mechanical strength, and investigate the benefits of the addition of lime in the mix, a combination of lime treatment and cement

Table 2
Physical characteristics of D1

Parameters	Value
Water content (%)	156
Grain sizes	
(%) < 2 μm (clay)	5.4
2 μm < % < 63 μm (silt)	57.8
63 μm < (%) (sand)	36.8
ρ_s (kg/m^3)	2530
Methylene blue	3.1
w_L (%)	97.4
w_P (%)	45.0
IP (%)	52.4

treatment was also considered. The lime quantity added to mix 2 was defined on the basis of a Lime Fixation Point (LFP) test (Tremblay, 1998). In this test, sediments and lime are mixed in demineralised water. The liquid-to-solid ratios of 2.5 and 5 are used, and the lime content is calculated on the basis of the dry weight of the sediments.

3. Results

3.1. Design of the material

The optimization procedure based on the grain size distribution (Fig. 2), the amount of fine dredged sediment in the mix, and the decrease in the water content of the fine sediments resulted in a mix denoted as mix 1, made of 33% fine dredged sediments, 61.3% dredged sand, and 5.7% cement.

The second mix, denoted mix 2, is based on the same proportions of fine dredged sediments, dredged sand, and cement as mix 1, to which a proportion of lime is added. The proportion of quicklime in the mix is fixed based on the LFP test as described above. As shown in Fig. 3, for both liquid-to-solid ratios investigated, the measured pH reaches a maximum value for a lime addition of about 3% of the dry mass of raw fine sediments. As the fine dredged sediments constitute one-third of the dry mix, the minimum lime proportion to be added to reach the LFP is about 1% of the dry mass of the mix. To ensure beneficial impacts of the lime in the mix in terms of mechanical strength improvement, the lime proportion was fixed at about 2% of the dry mass. This amount of lime associated with the cement is typical of proportions usually used for fine soils on building sites (CFTR, 2007; DREIF and LROP, 2003).

Fig. 4 shows the particle size distributions of the two mixes and the used lime. Proportions of the components in the two studied mixes, by dry mass, are reported in Table 3. In addition, corresponding values of Cu and Cc are shown. The two mixes respect the uniformity and curvature criteria according to the USCS classification.

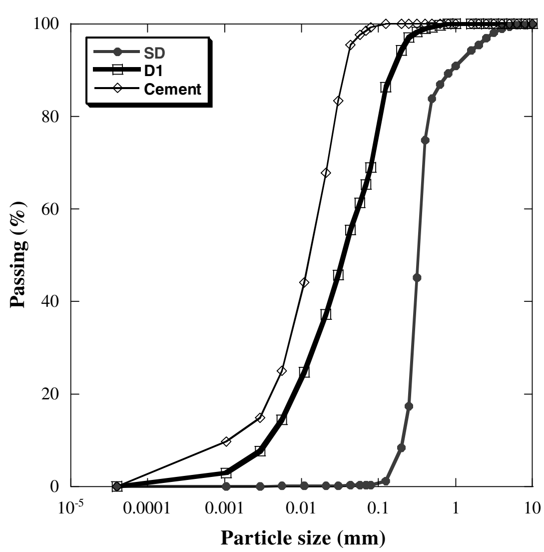

Fig. 2. Size distributions of the various granular elements added into the mixes.

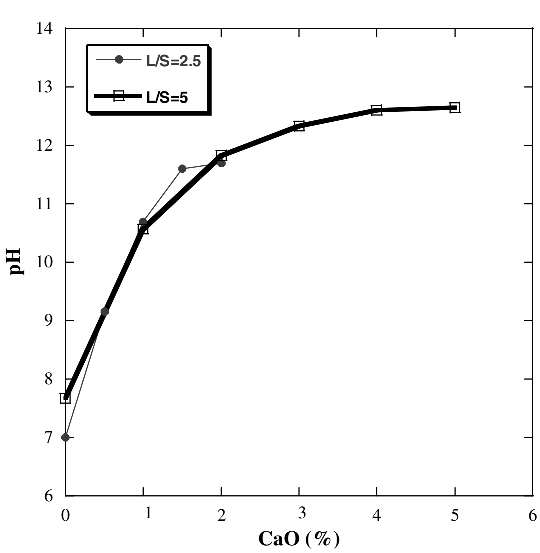

Fig. 3. Evolution of the pH for a sediment solution according to the lime addition.

3.2. Study of the mechanical behaviour of the materials

To explore the suitability of the defined mixes to be used as pavement base material, the mechanical behaviour of the designed material was studied according to the French Standard NF P 98 114-3 (AFNOR, 2001a). The main mechanical characteristics that define the ability of the material to be used in pavement base are, in the case of this study: (1) the CBR index, (2) the tensile strength (usually measured with Brazilian tests), and (3) Young's modulus.

3.2.1. CBR index

The California Bearing Ratio (CBR) is used to measure the bearing capacity of a compacted material. This test consists of applying a static load with a piston and to follow the penetration of this piston into a material. This test is preceded by the compaction of samples according to Proctor tests, which are necessary to evaluate the water content, allowing the highest level of compaction at a field site.

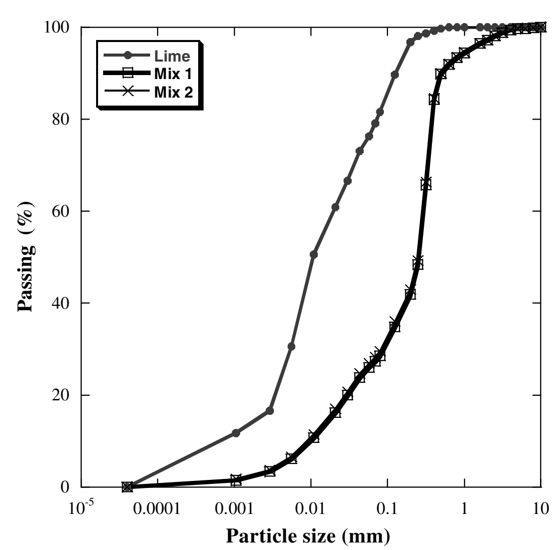

Fig. 4. Size distributions of the two studied mixes and the lime.

Table 3
Proportions of each element compounding the mixes–coefficients of uniformity and curvature

Mix	Sediments (D1)	Dredging sand (SD)	Cement	Lime	Cu	Cc
1	33%	61.3%	5.7%	0%	29.6	2.8
2	32.4%	60.2%	5.6%	1.8%	31.6	2.6

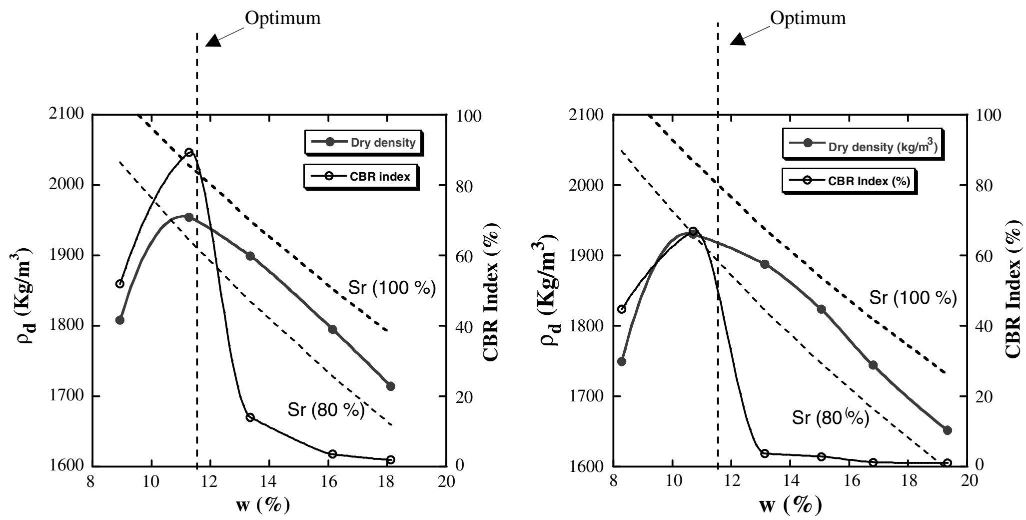

Fig. 5. Level of compaction and bearing of mix 1 (left) and mix 2 (right).

Test results of both mixes following test standard NF P 94 093 are shown in Fig. 5. The optimum level of compaction is evaluated by following the evolution of the dry density with the help of the saturation curves, which represent the theoretical density evolution of the material with a saturation (Sr) of 100% (no air voids) and 80% (80% water filled voids and 20% air filled voids). According to the corresponding value of moisture content, the CBR index is determined.

For both the mixes, similar optimum moisture contents and similar dry densities at the optimum moisture contents are observed. Table 4 shows that the optimum moisture content and the optimum dry density is similar for the two mixes and is not affected by the addition of lime in mix 2. At the optimum moisture content, the CBR indexes are about 82% and 50% for mix 1 and mix 2, respectively. These high CBR values ensure the trafficability of machines during the road work. It should be noted that the bearing ratio of the raw sediments was almost three times lower than that of the mixes.

3.2.2. Tensile strength and Young's modulus

The tensile strength, R_t (in MPa), is obtained by the diametrical compression test (AFNOR, 2001b), using Eqs. (3) and (4):

$$R_{tb} = 2 \times 10^{-2} \frac{Fr}{\pi \phi h} \tag{3}$$

$$R_t = 0.8 \times R_{tb} \tag{4}$$

where R_{tb} is the indirect tensile strength in MPa, Fr is the radial force applied in N, φ is the diameter of the cylindrical sample in centimeter, H is the height of the cylindrical sample in centimeter.

The Young's modulus is measured with an unconfined compression test and is defined as the slope of the stress-strain curve for stresses up to 30% of the maximum strength (AFNOR, 1991).

Test results of tensile strength and the Young's modulus of mixes 1 and 2 after curing periods of 7, 28, and 90 days are shown in Figs. 6 and 7. The estimated values at 360 days, which are used

Table 4
Dry density, water content and CBR index for the highest level of compaction

Mix	1	2
ρ_d (kg/m^3)	1960	1960
Water content (%)	11.5	11.6
CBR index	82	50

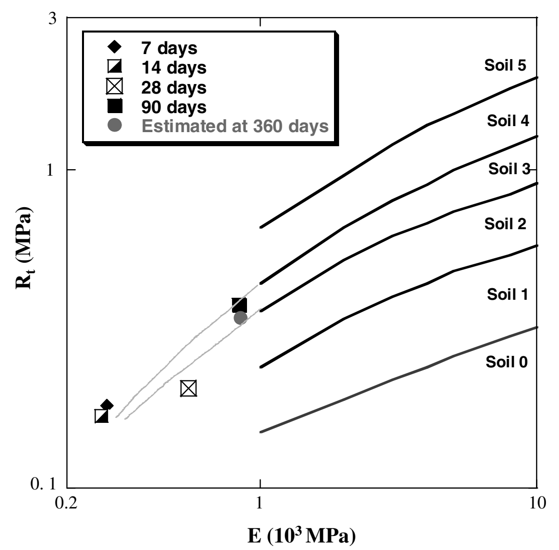

Fig. 6. Evolution of the mechanical behaviour of the mix 1 with time.

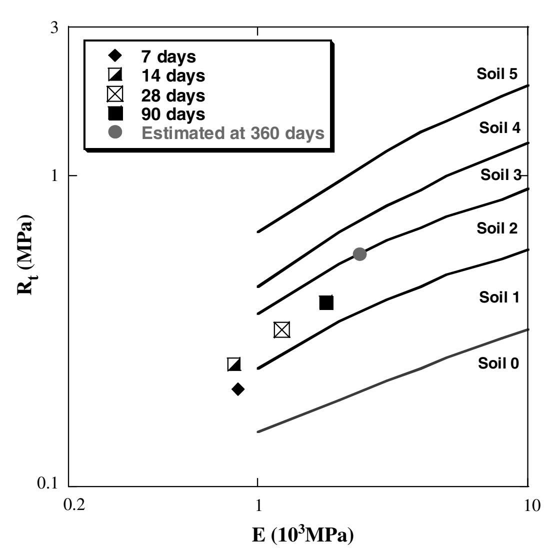

Fig. 7. Evolution of the mechanical behaviour of the mix 2 with time.

as the time reference for classifying road materials, are also reported. It should be noted that the estimated values at 360 days for materials treated with cement are calculated from measured values at 28 days according to Eqs. (5) and (6) (AFNOR, 1994a). For materials treated with lime and cement, the estimated values at 360 days are calculated from measured values at 90 days according to Eqs. (7) and (8) (AFNOR, 1994a). On the same figures, the limits for different material classes, as defined by test standard NF P 98 114-3 (AFNOR, 2001a), are shown.

$$\text{At 28 days,} R_t/R_{t360} = 0.60 \quad (5)$$

$$E/E_{360} = 0.65 \quad (6)$$

$$\text{At 90 days,} R_t/R_{t360} = 0.70 \quad (7)$$

$$E/E_{360} = 0.75 \quad (8)$$

From these results (Figs. 6 and 7), it is interesting to note the beneficial impacts of the lime in mix 2 in the early stage and on the long-term behaviour of the designed material. In the early stage, the lime enhances the cement hydration by reducing the negative effects of organic matter, whereas in the late stage, the lime (in excess) develops pozzolanic reactions. For mix 1, the values at 360 days estimated from the test results at 28 days are almost reached after 90 days. For mix 2, a monotonic increase of the material characteristics is observed.

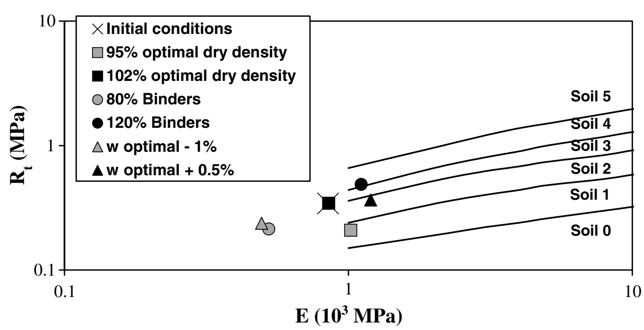

Fig. 8. Influence of the variability of dry density, binder proportion and water content on the mechanical behaviour of mix 1.

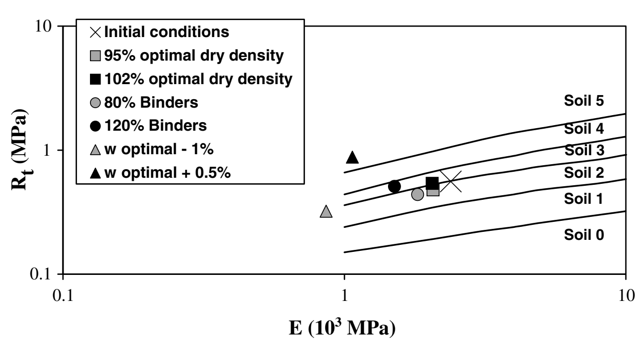

Fig. 9. Influence of the variability of dry density, binder proportion and water content on the mechanical behaviour of mix 2.

In order to study the stability of the mixes, a parametric study was performed according to test standard NF P 98 113 (AFNOR, 1994a). For each mix, the effects of three parameters were evaluated: optimal dry density, hydraulic binder amount, and water content. The test results are reported in Figs. 8 and 9, respectively, for mixes 1 and 2. The test results classify both mixes as at least class 2 materials.

3.2.3. Resistance to wetting and freezing cycles

In order to investigate the durability of the designed material, the sensitivity to water and to thawing–freezing cycles was evaluated.

The sensitivity to water was evaluated by comparison of the CBR index before and after immersion in water for 4 days according to test standard NF P 94 078 (AFNOR, 1997). The test results, in terms of water content before and after immersion, dry density, the CBR index before and after immersion, and swelling of the samples, are reported in Table 5. For comparison, test results on raw material are also reported.

In terms of the CBR index before and after immersion, the test results show a significant increase for both mixes 1 and 2. For the raw materials, the CBR index before immersion is very low and decreases after immersion. In terms of the swelling property, the measured values on the mixes are about 0.03%, whereas for the raw material a swelling value of 2% was measured.

The sensitivity of the material to thawing–freezing processes was evaluated by measuring the strength in compression after 20 freezing–thawing cycles according to test standard NF P 98 234-1 (AFNOR, 1992). This test is performed on cylindrical samples stored at 20 °C for 28 days. Half of the samples are then subjected to 20 freezing–thawing cycles in a climatic chamber while the other half are kept at 20 °C. A freezing-thawing cycle lasts 24 h; during the first stage, which lasts 4 h, the sample is maintained at a temperature of 10 °C, then during the second stage, which lasts 14 h, the sample is kept at −10 °C. The remaining time allows the transition between the two stages.

For the two mixes, six cylindrical samples (φ = 10 cm, h = 20 cm) were prepared by vibro-compaction; three were subjected to the freezing–thawing cycles while the remaining three were kept at 20 °C.

Test results in terms of measured unconfined compression strength are reported in Table 6. From these results, it appears that the designed materials are insensitive to freezing–thawing cycles, as the unconfined compression strength is almost the same for both series of tests.

Table 6
Resistance of mixes to cycles of freezing–thawing

Conditions	Mix	Rc (MPa)				
		Sample 1	Sample 2	Sample 3	Mean	Standard deviation
Freezing–thawing	1	1.64	1.42	1.58	1.55	0.11
	2	1.27	1.83	1.62	1.57	0.28
Normal conditions	1	1.64	1.96	1.80	1.80	0.16
	2	1.29	1.72	1.31	1.44	0.24

Table 5
Resistance to immersion of raw sediments and studied mixes after compaction

		Initial water content (%)	Dry density (kg/m^3)	I_{CBR}	I_{CBR} after immersion	Swelling (%)	Water content after immersion (%)
D1	Normal proctor	24.8	1350	9.0	2.5	1.97	35.0
Mix 1	Modified proctor	13.3	1910	30.0	173.0	0.03	13.0
Mix 2	Modified proctor	13.0	1910	25.0	127.3	0.03	13.2

Table 7
Analysis of physico-chemical elements in leachate after leaching tests on monolithic and crushed samples with the mix 2

Conditions	Monolithic samples			Crushed samples		
Laboratory	EMD	INERTEC		EMD	INERTEC	
Maturation	28 days	28 days	60 days	28days	28 days	60 days
Soluble fraction (mg/kg)	/	«6300»	«5700»	/	«28,400»	«28,200»
pH	[11.83]	[11.44]	[10.11]	[12.62]	[12.59]	[11.72]
As (mg/kg)	[<0.5]	[<0.05]	[<0.05]	[<0.5]	[<0.05]	[<0.05]
Cd (mg/kg)	[<0.1]	[<0.05]	[<0.05]	[<0.1]	[<0.05]	[<0.05]
Cr (mg/kg)	[<0.1]	[<0.05]	[<0.05]	[<0.25]	[0.14]	[0.10]
Cr(VI) (mg/kg)	[<0.1]	/	/	[<0.25]	/	/
Cu (mg/kg)	[<0.5]	[<0.05]	[<0.05]	[<0.5]	[<0.2]	[0.30]
Hg (mg/kg)	[<0.01]	[<0.05]	[<0.05]	[<0.01]	[<0.05]	[<0.05]
Ni (mg/kg)	[<0.4]	[<0.05]	[<0.05]	[<0.4]	[0.26]	[0.28]
Pb (mg/kg)	[<1]	[<0.05]	[<0.05]	[<1]	[<0.05]	[0.27]
Zn (mg/kg)	[<0.5]	[<0.05]	[<0.05]	[<0.5]	[<0.05]	[0.07]
Fluorides (mg/kg)	[1]	[<0.5]	[2]	/	[9.6]	[8.3]
Chlorides (mg/kg)	«2783.3»	/	/	«6916.7»	/	/
Sulphates (mg/kg)	[60]	/	/	[340]	/	/
Phenol index (mg/kg)	/	[<0.5]	[0.6]	/	[<0.5]	[1]
TOC (mg/kg)	[58]	[58]	[64]	/	[355]	[495]

References	Pollution level					
European directive 2003/33/CE (JOCE, 2003)	Low	Class III Inert waste [ ]	Class II Non-dangerous waste « »	Class I Dangerous waste §§	Treatment to store ▹◃	High

3.3. Environmental impact of designed material

An environmental impact study on the designed road material was performed by two different laboratories (Ecole des Mines de Douai and INERTEC laboratory). The experimental program was composed of leaching tests on monolithic samples according to test standard NF X 31 211 (AFNOR, 1994b), and leaching tests on crushed samples according to test standard EN 12457-2. The results are shown in Table 7.

For the raw sediments, the proportions of antimony (Sb), barium (Ba), molybdenum (Mo), and selenium (Se), as well as organic parameters in the solid matrix, were not determined because of their very low proportions in the raw sediments.

The results show high values of chlorides and soluble fractions, classifying the mix as non-dangerous waste according to the decision of the European Council (2003/33/CE) concerning waste disposal sites. The sulphate contents conform to the specifications for inert wastes.

4. Discussion

To use fine dredged sediments in road construction, it is necessary to first reduce the initial water content of the material. In this study, consolidation under self-weight and evaporation at 40 °C in the laboratory were investigated. The efficiency of the proposed methodology was explored on site in the framework of the preparation of materials for building an experimental road (Zentar et al., 2008). In this case, two storage zones were defined. In the first zone, the dredged sediments were placed in a 2 m thick layer. After a consolidation period of four weeks and to accelerate the evaporation, the fine dredged sediments were placed in the second zone, on top of dredged sand in a thin layer about 0.2 m thick. This system reduced the water content of the fine sediment on site to the desired value. At the industrial scale, the dewatering process could be further enhanced by mixing the dredged sand with the fine sediments while wet. In this case, by increasing the permeability of the fine sediment, the efficiency of the consolidation under self-weight could be enhanced. Additional studies could be carried out to evaluate the performance of mixes with variable proportions of fine sediments at different water contents.

In the framework of the design of mixes for road materials, the use of dredged sand allows us to propose an alternative solution for better management of dredged materials of both types of sediments. Moreover, the mix could be made on site, which can enhance the consolidation under self-weight and reduce the costs of the proposed mixes. The methodology proposed to design the mixes and the amount of binders used in the proposed mixes make the beneficial use of dredge sediment economically viable.

In terms of the CBR index curves, similar results were observed for both mixes. A rapid increase of the I_{CBR} was observed for a small decrease of water content, with values close to the optimum water content w_{OPM}. The water content corresponding to the beginning of the I_{CBR} increase is in the range of 13.5–14%, and seems to be dependent on the proportion of fine sediments (32.4–33%) and on the plastic limit (45%). Indeed, if the plastic limit is balanced by the proportion of fine sediments, the obtained value, between 14.6% and 14.9%, is in the same range. Hence, in order to ensure sufficient bearing capacity, it is necessary that the water content of the fine sediments, balanced according to their proportion in the mix, are equal or inferior to the plastic limit of the sediments.

In terms of material classification from the estimated values of the mixes at 360 days, mix 2 is on the limit between class 2 and class 3, whereas the results of mix 1 are heterogeneous and vary between classes 1 and 2 limits and between classes 3 and 4 limit (Figs. 6 and 7). It should be noted that the minimum class required for a material to be used in a sub-base is class 2. Thus, mix 2 is more appropriate to use as a pavement base.

The increases of mechanical strength are similar for the two mixes. However, the addition of lime in mix 2 strengthens the material. As discussed by Clare and Sherwood (1954), the lime probably improves the development of bonds by reducing the effects of organic matter on the cement hydration throughout the increase of calcium ions in the aqueous phase.

It should be noted that the mechanical strengths obtained are close to the values for treated soils as reported in the guide of materials of "Ile de France" (DREIF and LROP, 2003). In this guide, minimum values of E and R_t (at 360 days) for treated soils are in the range 4.6–5.3 GPa and 0.49–0.56 MPa, respectively, depending on the bearing of the sub-grade.

The parametric study performed on the designed materials did not reveal prejudicial sensitivity to variations of dry density, binding proportion, and the water content in the ranges explored. The sensitivity to water content study and the freezing study demonstrated a good behaviour in conditions of frost, and no swelling problems were recorded. To complete the mechanical characterization, the material resistance to cyclical loading could be studied.

Test results for monolithic and crushed samples, shown on Table 7, appeared homogeneous, and the designed materials can be classified as non-dangerous wastes according to the physico-chemical indicators. In comparison with the considered elements of the French circular on the re-use of MSWI bottom ash (DPPR/SEI/BPSIED No. 94-IV-1), the pollution level of the designed road material in this study corresponds to category "V", which is allowed for use in road construction.

If the environmental test results on the raw sediments (Table 1) are interpolated with the proportion of fine sediment in the studied mix (Table 3), the estimation of the chloride and sulphate contents is higher than the measured results (Table 7), which indicates the efficiency of the decantation coupled with the treatment by hydraulic binders.

On the basis of this study, the developed mixes could be studied with more polluted sediments to evaluate the efficiency of the proposed solution and the influence of other pollutants in the matrix.

5. Conclusions

For harbour managers, better management of dredged materials constitutes a key requirement to maintain navigation and to accommodate sustainable development. In this paper, an alternative solution for re-use of dredged sediments (fine dredged sediments and dredged sand) in road construction is proposed.

The methodology implemented in this study to develop the designed mixes consists of dewatering the fine sediments by decantation and improving the granular distribution by adding dredged sand. The initial decantation process is necessary to reduce dissolved salts in the pore water. The enhancement of the granular distribution improves the bearing capacity of the dredged sediments and reduces the amount of binders needed to meet the performance prescribed for the targeted use. In this study, the amount of binders added to the proposed mixes is comparable to the amount used in standard materials. These results make the designed mixes economically viable.

In terms of environmental impacts, the values of chlorides and the soluble fraction classify the mix with lime as non-dangerous material. According to French legislation of MSWI bottom ash this mix can be used as road material.

On the basis of these results, the proposed methodology could constitute a starting point for the investigation of possible beneficial uses of polluted sediments in the field of road construction.

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