STUDY OF THE PHYSICAL AND MECHANICAL PROPERTIES OF ROAD GRAVEL RECONSTITUTED FROM DREDGED MARINE SEDIMENT AND SAND

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Abstract

In France, over 400 million tonnes of granular materials are used in civil engineering of which over half is used in road construction and in same time dredging operations generate each year, more than 50 million m3 of marine sediments. The use of these sediment volumes will preserve natural resources and contribute significantly to environmental preservation. Dredged sediments are characterized by a high fine fraction and a high content of organic matter. Thereby, the raw sediments can't be used in road construction without a specific treatment process. In order to improve the physical and mechanicals sediments characteristics, addition of a granular material is recommended. The use of a dredged sand to improve the granular mixture containing sediments allows a better management of the two types of dredge materials (sand and sediment). This paper carried out the effect of different percentage of dredging sediments on physical and mechanical parameters of the mixtures (granular parameters, compactness, porosity, compaction parameters, and shear behaviour parameters). The results show that the mixture of 40 % of sediment and 60 % sand fulfils the requirements for the application in road sub layer.

Keywords: dredging materials, triaxial test, geotechnical parameters, packing density model

1. Introduction

Dredging is a vital operation for the exploitation of port infrastructures. Worldwide over 600Mm^3 of sediments are dredged annually of which 20% are contaminated (Miraoui, 2012). France with over 6500km of coast dredges an average of 50Mm^3 of sediments per year (Levacher *et al.*, 2009). With increasingly stricter laws aimed at conserving the environment and aquatic habitats and the prohibition on dumping at sea beyond a certain pollution threshold, the management of dredged sediments on land has become even more essential. In France, over 400 million tonnes of granular materials are used in civil engineering of which over half is used in road works (Zentar *et al.*, 2009). A stone skeleton is optimised to define a flat grading curve which ensures a minimum of gaps and consequently, maximum compactness. The literature contains several references for establishing good particle size composition. This study uses reference curves also called Talbot-Fuller-Thomson (TFT) curves to verify the spread of grading curves for the studied mixes. Mixes were based on stone skeleton optimisation results according to the packing density (De Larrard, 2000). The influence of adding a particle size corrector on mix properties is studied through the following three parameters:

- **Particle size criteria** : coefficients of uniformity Cu and curvature Cc,
- **Compaction parameters** : dry density and Immediate Bearing Capacity
- **Shearing parameters**: friction and cohesion angle.

2. Methods and materials

a. Materials characterisation

For dredged sediment, the physical characterisation consist to the determination of the grains size distribution [NF ISO 13320-1], the water content [NF P 94-050], the Atterberg limits to determine the parameters of plasticity of sediment [NF P 94-051]. The liquid limit (*LL*) was measured by using the Casagrande equipment and the plastic limit (*PL*) by the technique of the rollers. Then the absolute density is estimate by helium pycnometer [NF P 94-050]. The loss on ignition was determined to evaluate the organic matter content in sediment [NF EN 12879]. These tests permitted to classify the dredged sediment in medium organic soil type according the GTR Guide (SETRA-LCPC, 1992). The mechanical characteristics behave in this study to determine the Proctor Optimum and CBR Index to sediment [NF P 94-093]. For this material, a typical grain size distribution is shown in Figure 1 and the main physical characteristics are summarized in Table 1. The fine dredged sediments are composed mainly of silt with a high value of the liquid limit. The organic matter content measured is small than 6%.

Table 1. Physical and mechanical characteristics of raw sediment

Samples	Raw sediment
OM (%)	5.4
0/2µm fraction (%)	19.6
2/63µm fraction (%)	31.4
63/2µm fraction (%)	49.0
0/80µm fraction (%)	77.0
ρs (Mg/m3)	2.53
LL (%)	57
PI (%)	20
MBV (g/100 g)	1.4
WOPN (%)	21.5
ρd(Mg/m3)	1.51
IBI	10.5

The triaxial test is used to perform compression tests on cylindrical samples of material. Radial confining pressure was applied to the cuvettes containing the samples in each test. The setup comprises a triaxial press able to deliver a pressure of 50 kN, a triaxial cell and a measurement system. The press, constituting the rack, is a controlled speed electromechanical press. The cell, placed on the press, can take cylindrical samples 100mm high and 50 mm in diameter. The water-filled cell is pressurised to apply confining stress. The cell is also equipped with two pressure sensors to measure confining pressure and pressure inside the sample, that is, counter pressure. These two pressures are supplied by a compressor with air-water regulators and interfaces. The counter pressure sensor also serves to measure interstitial pressure in the case of a non-drained test. Shearing strength is measured by a force sensor placed at the top of the press frame. Vertical displacement of the sample is measured by an LVDT displacement sensor. This data is recovered by a GDS-type data logging system used to collect data from the rammers, the pressure sensor, the axial displacement sensor and the force sensor. All this data is managed with GDS lab software.

In this experimental work the granular corrector was used to study their influence on compactness and on treatment performance. This granular corrector is constituted by dredged sand for 0/2 mm class.

b. Mix design

With the Packing density model applies well for the formulation of mixtures of classes and different granular compactness. The objective of the method consists to maximize the compactness of the granular skeleton of mixture by optimizing the proportions of the various size ranges (sand, sediments). The model was proposed by De Larrard (2000). This model makes it possible to determine the real compactness of a mixture starting from the knowledge of its virtual compactness and the K index associated with the mode of mixtures compaction. According of De Larrard (2000), the relation between the K index of tightening and real compactness was:

$$\boldsymbol{K} = \sum_{\boldsymbol{i=1}}^{\boldsymbol{n}} \frac{\frac{\boldsymbol{yi}}{\boldsymbol{\beta}}}{\frac{\boldsymbol{1}}{\boldsymbol{\varphi}} - \frac{\boldsymbol{1}}{\boldsymbol{\gamma i}}} \qquad eq.1$$

K: tightening index which only depends on the energy of compaction,
γi: virtual compactness when class i was dominant,
n: number of classes in the mixture,
βi: residual compactness of the class i,
yj: volumetric proportion of the class j in the mixture
Φ: real compactness of the mixture of n classes.

3. Results and discussion

3.1. Evolution of the compactness and porosity of mixtures

Within this framework, it was prepared several dry mixtures containing sediments and of dredged sand with different proportions according the following steps:

First step: for the experimental determination of the compactness of the mixtures for each mixture, a sample of 1.2 kg with the proportion given of the components is selected. After manual homogenisation during 5 minutes, the mixture is set up under an average pressure of 10 MPa applied by static compression. For this, quantity of 400 g was necessary for the manufacturing of a cylindrical test-tube (5 cm x 10 cm). The experimental compactness of each mixture is calculated by dividing the mass of the sample by the average density of the aggregate, then by its total volume. Each experimental value taken into account in the model is the average of three measurements.

Second step: Theoretical determination of the compactness of the mixtures to carried out simulations a computation software was used. This software was developed at the central laboratory of the bridges and road way (LCPC-France), it is called Rene LCPC. The use of this software made it possible to find compactness theoretical of the various mixtures. The index of tightening used in calculations was equal to 7. This value was obtained by Miraoui (2012) by making a bringing together between the results of compactness got in experiments and the theoretical values obtained with various values of the index of tightening.

Table 2 shows the results of the calibration of the model the experimental and theoretical data of compactness and porosities of the studied binary mixtures. The standard deviation of measurements carried out is lower than 5%. The bringing together between the theoretical and experimental compactness values is illustrated in figure. The experimental results are always lower than the theoretical results that could be due to the difficulties met at the time of the realization of the tests. Knowing that the index of tightening is an intrinsic parameter of the method of installation of material, the comparison between the experimental and theoretical values makes it possible to confirm that an index of tightening equal to 7 translated perfectly the energy of static compaction under a pressure of 10 MPa. The observation of figure makes it possible to distinguish an optimum which makes correspond a proportion of sediments for which compactness is maximum. This proportion is about 40% of the total dry mass of the mixture. These results are in agreement with the results got in the previous studies (Dubois, 2006; Miraoui, 2009; Maherzi, 2013).

Table 2. Evolution of porosity and compactness of mixtures

Results	Experimental		Theoretical	
Sed. (%)	Poro.	Comp.	Poro.	Comp.
0	35.64	0.6436	34.96	0.6504
5	35.21	0.6479	/	/
10	35.04	0.6496	32.74	0.6726
15	34.42	0.6558	/	/
20	34.16	0.6584	31.00	0.6900
25	33.45	0.6655	/	/
30	33.65	0.6635	30.14	0.6986
35	33.58	0.6642	/	/
40	33.51	0.6649	30.43	0.6957
45	33.48	0.6652	/	/
50	33.81	0.6619	31.64	0.6836
60	34.45	0.6555	33.34	0.6666
70	36.49	0.6351	35.23	0.6477
80	37.10	0.6290	37.14	0.6286
90	39.24	0.6076	39.01	0.6099
100	40.87	0.5913	40.82	0.5918

3.2. Influence of adding a grading corrector on particle size criteria

For this part two mixtures were studied (M I: 30%SD+70%Sed; M II: 60%SD+40%Sed) according to different criteria. Figure 3 shows particle size distribution in the different studied mixes. Each curve represents an average of three grading curves obtained by analysis with a laser granulometer.

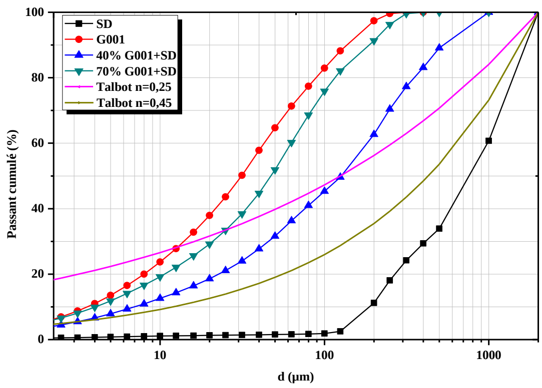

Figure 1. Granular distribution of different mixes

The curves Talbot - Fuller - Thomson means the optimal granular arrangement of granular mixtures. These curves are obtained for n values of 0.25 and 0.45, defining an optimum spread in grading curves. This spread represents an approximation to the ideal grading curve

$$P = \left[\frac{d}{D}\right]^n \times 100 \qquad \text{eq. 2}$$

Where:

D: the maximum diameter taken equal to 2 mm,
d: sieve size (mm),
P: percentage (%) of particles passing through according to sieve size d,

The results show that the particle size distribution of mix (60% SD+40% Sed) is closer to the optimum Talbot-Fuller-Thomson range. Followed by mix I(30% SD+ 70% Sed.) and mix II, respectively. Calculation of grading and uniformity coefficients appears to be the best means of appreciating the difference between the particle sizes distributions presented above. Note that particle size is said to be uniform if the following two criteria are confirmed (Schlosser, 1988):

- 1<Cc<3: particle size distribution is said to be well graded,
- Cu>6: particle size distribution is said to be well spread.

Table 3 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 + spread) Therefore the addition of dredged sands in proportions equal to 60 and 30% appears to fulfil the above-mentioned particle size conditions.

Table 3. Curve and uniformity coefficients for the different mixes

Coeff.	Sed.	SD	M I	M II
Cu	11.9	5.2	15.5	23.4
Cc	1.2	0.9	1.7	1.4

M I: 30%SD+70%Sed; M II: 60%SD+40%Sed

3.3. Influence on compaction parameters

Proctor Optimum Value compaction parameters bearing capacity are shown in Figures 2 and 3 and in Table 4. Adding dredged sand increases dry density and bearing capacity and reduces optimum water content. In fact, the Proctor optimum dry density value goes from 1.51 t/m3 for raw sediment to 1.73 and 1.75 t/m^3 in mixes II and III respectively. Note that the Proctor optimum dry density values for mixes II and III remain comparable. CBR Index goes from 10.5% for raw sediment to 17.5 and 26.8% for mixes II and III. Optimal water content goes from 21.5% for raw sediment to 15.0 and 14.1% for mixes II and III respectively. Observation of these results suggests the same conclusions as those formulated by Dubois (2006):

- In a mix containing dredged sediments, the higher the sediment content, the higher the optimum water content and in parallel optimum dry density and optimum IBI are lower.
- We note also that CBR Index varies sharply in a relatively low water content interval. Dredged sediments and sediment-based mixes are sensitive to water and their use in road construction requires treatment with binders. This sensitivity can be linked to the presence of organic matter whose water retention ability increases the phenomenon.

Table 4. Compaction parameters for sediment, mixes and dredged sand

Mixes	W_{OPN} (%)	ρ_d (Mg/m^3)	Bearing Index (%)
Sed.	21.5	1.51	10.5
M II	15.0	1.73	17.5
M III	14.1	1.75	26.8

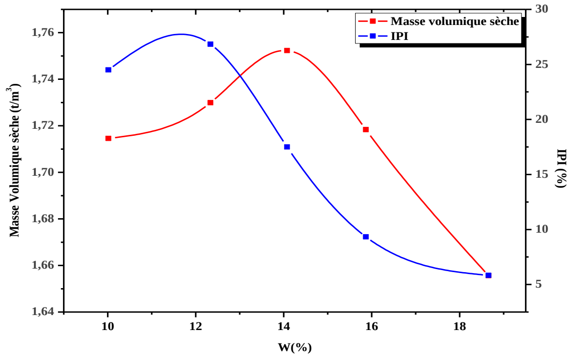

Figure 2. Proctor-IBI curves for mix II (40% Sed. and 60% D.S.)

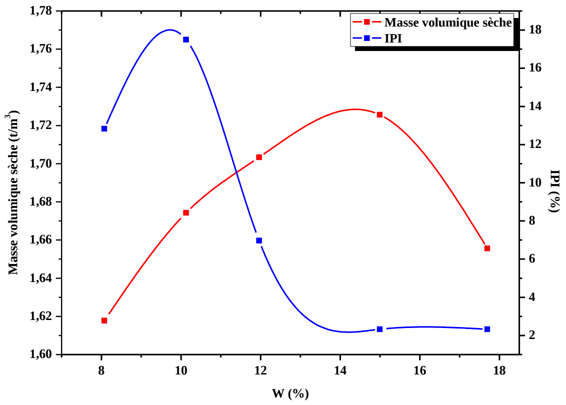

Figure 3. Proctor-CBR Index curves for M I (70% Sed. and 30% D.S.)

3.4. Influence on shearing characteristics: triaxial test

This study examines the influence of adding a grading corrector on intrinsic shear characteristics, that is, cohesion (C) and the internal friction angle (φ) of the mixes. The three mixes presented above were studied with a triaxial apparatus. Non drained triaxial test results for the three samples are presented below:

The test was carried out for three levels of confining stresses of 300, 400 and 500 kPa which correspond to a normally consolidated domain. Break load was reached each time. Figures 4, to 7 show the relation between axial deformation and diverter q. In all the tests, two phases were observed:

- an initial phase that corresponds to the fast evolution of q in relation to axial deformation ε_a,
- a second phase where deviatoric stress q stabilises while axial deformation continues to grow. This phase begins when break load is reached.

The above results show that tensile strength is inversely proportional to the proportion of sediments in the mix. Thus the fine fraction consisting mainly of sediment has an adverse effect on the behaviour of the material under compression

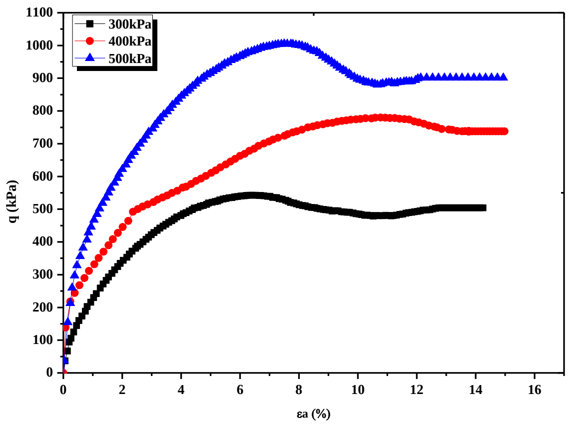

Figure 4. Relationship between deviatoric stress q and axial deformation ε_a of dredged sand (DS)

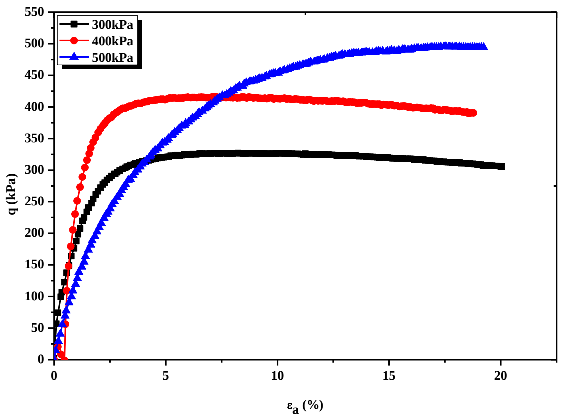

Figure 5. Relationship between deviatoric stress q and axial deformation εa for mix II

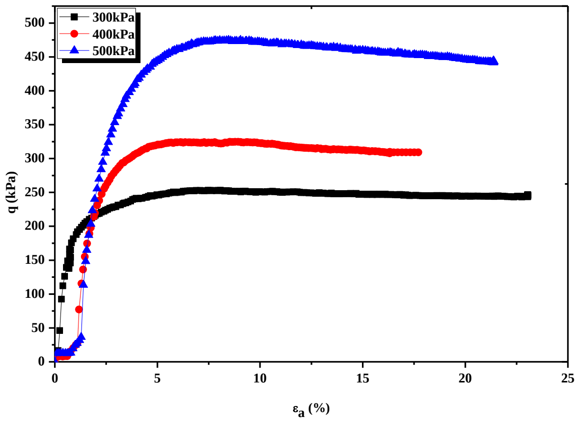

Figure 6. Relationship between deviatoric stress q and axial deformation εa for mix I

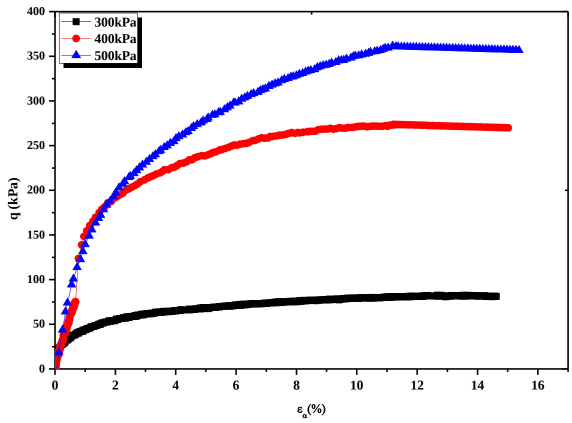

Figure 7. Relationship between deviatoric stress q and axial deformation ε_a for raw sediment

Figure 8 shows observation of the samples after fracture. Two types of fracture appear:

- Brittle fracture of the samples of dredged sand characterised by a sideward 45° crack.

- Ductile fracture of the samples of raw sediment

characterised by fracture due to expansion.

Figure 8. State of samples shall (right: dredging sand, left: dredging sediment)

Axial and radial deformations represent the sums of relative deformations between two measurement points:

$$\varepsilon_a = \sum_{i=0}^{n} \frac{H_i - H_{i-1}}{H_{i-1}} \qquad \text{eq. 3}$$

$$\varepsilon_r = \sum_{i=0}^{n} \frac{D_i - D_{i-1}}{D_{i-1}} \qquad \text{eq. 4}$$

Heights H_i are obtained by subtracting axial displacement measured at instant i by the displacement sensor from the initial height. Diameters D_i are calculated from area A_i on the transversal surface of the sample which depends on the volume and height of the sample at instant i. For all the tests performed, the ratio between radial and axial deformations is 2 which confirms the test conditions and in particular the absence of drainage (Figure 9). In fact, under these conditions volume deformation ε_V is considered equal to 0. Axial deformation is then compensated by a radial deformation (Dubois, 2006; Wang, 2010). In three dimensional spaces, volume deformation is the sum of deformations for each axis. Radial deformation is then equal to the sum of deformations in the plane perpendicular to the application of pressure and axial deformation is the deformation associated with the point where pressure is applied. Deformations on each axis are equal to each other and $\varepsilon_r=-2\varepsilon_a$.

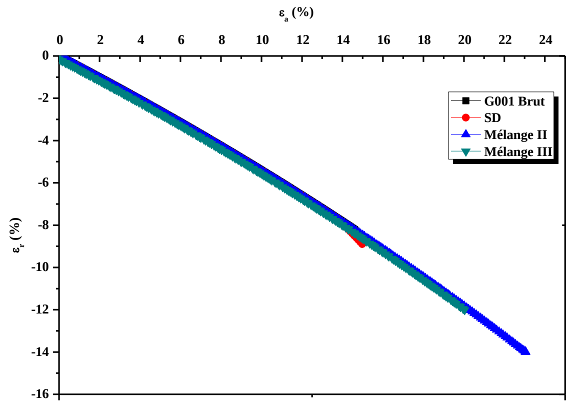

Figure 9. Relation between radial deformation ε_a and axial deformation ε_a

Shearing parameters were determined using total stresses. The results are shown in Table 5. In comparison with the results of the study by Dubois (2006) and Wang (2012), raw sediment has a lower friction angle in relation to the Dunkirk port sediments (France) and cohesion is close to the values found by Dubois (2006). This result is due to the fact that shearing characteristics depend on particle size (fine fraction), the shape of the solid grains and organic matter content in each dredged sediment studied. Following the tests on different mixes, the results suggest the following:

- For the two proportions of added dredged sand (30 and 60%) the friction angle for the mixes is close to the friction angle for the sediment,
- In contrast, the cohesion of sediment-SD mixes is close to that of dredged sand.

Table 5. Intrinsic shear characteristics of the mixes

	Sed.	SD	MI	MII
Friction angle (°)	12	33	14	17
Cohesion (kPa)	30	18	20	20

4. Conclusion

The following conclusions are drawn:

1- Geotechnical characteristics of the sediments are inadequate for use in the rough state in the geotechnical application,
2- The use of a granular addition as dredging sand allows for better characteristics,

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