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Economical approach and validation of treatment methods using binders of contaminated marine sediments

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Abstract:
For a better environmental practice in the land management of contaminated sediments considered as waste material, a pilot plant with sediments processing units was installed on a port site near the city of Toulon in the south of France. A large panel of sediments, representative of their variability, has been gathered on this pilot area to be treated and reused. All these processing operations constitute the basis of the SEDI.MAR.D. 83 programme. As part of this programme, one of the objectives concerns the valorisation of marine sediments with hydraulic binders. To succeed in doing that, feasibility tests of stabilization/solidification with raw or pre-treated sediments have been performed. Mechanical and environmental aspects were considered together with the different applied treatments. A lot of tests were run on various port sediments. The obtained results which follow were analyzed and have lead to studying the technical feasibility and ability of the process using hydraulic binders. On one hand, the optimization of the percentages of each binder and additives, if used, was searched for the different mixtures. On the other hand, the environmental acceptability was checked with regards to the enforced regulations, with a view to reusing the treated sediments as material. The considered beneficial uses concern roads and embankments constructions, mainly earthworks, landscaped slopes, fillings of quarries or underground holes. The possible reuses are discussed here and finally, a simple economical approach is proposed taking into account the different ways of treatment applied to the sediments before the stabilization/solidification by binders. This paper is one of a series relative to the SEDI.MAR.D. 83 project, (AQUA *et al*, 2009; BENOIT-BONNEMASON *et al*, 2009; LEVACHER *et al*, 2009; SEBY *et al*, 2009).

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1. Introduction

The dredging management of marine sediments contaminated by heavy metals, PAH and TBT substances, organic matters (SANNIER, 2008), poses technical and economical problems for the development and maintenance of port activities. Faced with this situation, for which it is forbidden to dump contaminated sediments at sea, port managers have reacted. They have initiated, in collaboration with maritime planning contractors, either research programmes or industrial projects to study and identify the possible beneficial reuses of these contaminated marine sediments on land. Note that on land, this type of sediments is considered as waste material according to French regulations. In this way, the Conseil Général du Var has proposed in 2002 an operational approach programme named SEDI.MAR.D. 83, (GROSDEMANGE *et al*, 2008, AQUA *et al*, 2009). This programme was carried out with different industrial and academic partners. One of the main objectives was to carry out tests on the selected contaminated marine sediments brought on the pilot site to be treated. All the tests are performed on hydraulic binder based mixtures in order to inert the pollutants contained in the sediments. The obtained by-products could be valorised mainly in road construction such as sub layers or embankments. So, considering sediments coming from different ports and combining various treatments for these before mixing with binders, a lot of tests were made to check the environmental and mechanical feasibility of the cement based and additives mixture processing (BOUTOUIL, 1998; COLIN, 2003; DUBOIS, 2006; SEMCHA, 2006; DUAN, 2008; TRAN, 2009).
Now, a stabilisation/solidification method using binders applied to the treatment of contaminated sediments must absolutely consider the following points of view, *i.e.* the technical aspect with the mechanical behaviour, the environmental acceptability in accordance with the present French regulations (ADEME *et al*, 2006) and finally, the taking into consideration of the economical approach (cost and competitiveness of the sub products or reused materials).
This paper is mainly focused on this economical study based on the use of different criteria. One concerns the evaluation by a weighted index of the applied treatment methods in relation with the mixture formulations (quantities of binders) and with the unconfined strength at 28 days noted Rc28. This Rc28 value constitutes a reference value for the road construction design. Although the environmental analyses are important in the valorisation of treated contaminated marine sediments, in this paper, only the mechanical and economical considerations are discussed. In fact, this paper is one of a series of contributions relative to the SEDI.MAR.D. 83 programme in which some of them will give in detail the results of the environmental analysis of the concerned Mediterranean sediments, (BENOIT-BONNEMASON *et al*, 2009; SANNIER, 2008; SEBY *et al*, 2009).
The cement-based mixtures are performed with sediments on which one or more treatments are applied before mixing. All these treatments are described as the

quantities of binders and additives used for the mixtures. Mixtures on raw sediments were also undertaken so as to be used as reference. Thus, an important experimental programme has been carried out, combining mechanical and environmental tests (SANNIER, 2008) for various formulations of binders and different pre-treatments applied to the sediments. These combinations were used thereafter as support with the suggested economic approach. This one is based on the definition of a weighted index or an economic note together with the formulations and the data processing sequences. An analysis of these economic evaluations follows which finally makes it possible to discriminate economically the pre-treatments run out making it possible to improve quality of the process by hydraulic binder.

2. Experimental case study

2.1 The object of the SEDI.MAR.D. 83 pilot plant

This study was prepared within the framework of a research and development programme called SEDI.MAR.D. 83 project to give some answers to the building owners for the management on land of the contaminated marine sediments. In France, the volume of this type of sediments is estimated at 10 million m^3 per year. The Conseil Général du Var has taken up its position as federator for the search of solutions. This experimental work is intended to test the technical and environmental feasibility of treatments with an aim of stabilizing the contaminants present in the marine sediments. These processes result in a controlled material which can be valorised according to these properties in the fields of civil engineering and construction like aggregates and/or construction material (LEVACHER *et al*, 2008a, 2008b and 2008c). Another beneficial use concerns the improvement of soils in agriculture.

The dredged sediments come from ten different but complementary sites in order to be representative of their variability. This variability obliges us to question the reliability of each valorisation process.

2.2 Description of the pre-treatment sequences

The ten harbour sediments sampled within the framework of this programme were submitted to various treatments preliminary to the addition of binder and this, individually. Thus, after reception on the pilot site, eight operations of pre-treatment were carried out either in a way independent from or following each other. Once arrived on site, the sediments go through a sieving and a hydro cyclone cutting and *de facto*, two classes of sediments are thus obtained: raw (sorting of coarse waste by sieving to 5 mm) and desanding (sorting by hydro cyclone with a cut at 63 µm) which contains the finest particles. The other operations apply then to these two categories of sediments. They will be carried out either alone in a single way, or in association, constituting a sequence of pre-treatments upstream before undergoing the treatment by hydraulic binder, see table I. In this programme, were thus carried out one operation or more relating to:

- a dehydration which is run out by mechanical filter pressing whose aim is the reduction of the water content and by consequence volumes to be treated,
- a composting over one four months duration in order to reduce the quantity of organic matter,
- a phosphatizing characterized by a phosphoric addition of acid to a proportioning of approximately 5%, to make the metal contaminants inert, (NGUYEN, 2008),
- a liming made up of an addition of 20% quicklime with an aim of destroying part of the organic matter and to lower the water content, (REY, 1999),
- a correction of granulometry with a contribution of a quarry material *i.e. a fine sand* of the same grain size distribution. The percentages of sand selected were respectively of 70% and 85% per 30% and 15% of sediment to be treated. This operation allows to improve the mechanical characteristics of material thus worked out, (COLIN, 2003; DUBOIS, 2006 ; TRAN, 2009),
- a calcination at a temperature of 450°C in order to destroy the organic matter and some contaminants, (NGUYEN, 2008).

In these pre-treatments, any operation of crushing or attrition was carried out on the sediments. Even if the attrition used in mineralurgic processes showed an interest for decontamination of storm water sediments (PETAVY *et al.*, 2007 and 2008). Table 1 gathers the different data processing sequences which the sediment underwent (pre-treatment) and the number of samples. Within the framework of the research works, all the sediments presented below were characterized from the chemical point of view before incorporation of cement. It was noted that none of the sediments whatever its class, and whatever the pre-treatments operated before cementing with binders, was reusable, (SANNIER, 2008). Indeed, none among them, did answer to the criteria of acceptability proposed for a road material valorisation (ADEME *et al.*, 2006) nor to the values thresholds of admission in centres of storage of waste according to the directive *landfills of waste* (OJEC, 2003). In addition, those showed a great diversity of chemical forms founded in heavy metals, (BENOIT-BONNEMASON *et al*, 2009; SEBY *et al*, 2009). However, it is not excluded that different behaviours can be observed during a treatment by binder related to the great variability of the states and levels of contaminations of the pre-treated sediments.

2.3 Methods

The treatment of the sediments by hydraulic binder is prepared according to two main mixtures, namely: mixtures “sediment and cement” and mixtures “sediment, cement and additive”. For these latter formulations, the objective is to study the influence of the presence of a certain quantity of additive reacting with the components of the sediment.

Table 1. List of the treatment processes and their symbols.

Abbreviations	***Chronology of treatments***	***Sample number***
DDCA	**D**ESANDED - **D**EHYDRATED – **CA**LCINED 450 °C	2
DD	**D**ESANDED – **D**EHYDRATED	6
DCO	**D**ESANDED – **CO**MPOSTED	11
BCA	**B** for RAW - **CA**LCINED 450 °C	15
BCO	**B** for RAW - **CO**MPOSTED	19
B	**B** for RAW	21
BPCO	**B** for RAW - **P**HOSPHATED – **CO**MPOSTED	24
DCH	**D**ESANDED – **CH** for LIMED	27
BCH	**B** for RAW - **CH** for LIMED	29
BCO-PD	**B** for RAW - **CO**MPOSTED – **P**HOSPHATED – **D**EHYDRATED	34
BCO **CG (MA)**	**B** for RAW – **CO**MPOSTED **C**ORRECTION of **G**RANULOMETRY (ALTERNATE **MA**TERIAL)	35
BCO-PD **CG (MA)**	**B** for RAW – **CO**MPOSTED - **P**HOSPHATED – **D**EHYDRATED **C**ORRECTION of **G**RANULOMETRY (ALTERNATE **MA**TERIAL)	36
DCO-P	**D**ESANDED – **CO**MPOSTED – **P**HOSPHATED	41
BPCO **CG (MA)**	**B** for RAW - **P**HOSPHATED – **CO**MPOSTED **C**ORRECTION of **G**RANULOMETRY (ALTERNATE **MA**TERIAL)	42
DPCO	**D**ESANDED – **P**HOSPHATED – **CO**MPOSTED	43

The components of the mixtures are introduced into a mixer in the following order: sediment, additive if it is necessary, then cement in order to respect the kinetics of the reactions involved. Cement used is a cement of the type CEM I PM 52.5 (CaO=65.3%). The two additives used are either a quicklime (CaO=92%) for its possible action on the organic matters, and incidentally on the improvement of the compressive strength; or a fly ash called Soproline® (fly-ash with 32.3% of CaO) to improve the pozzolanic reaction later on, by allowing in particular the particles of fly-ashes to be absorptive by those of cement and to prevent the better from flocculating. The formulations established in this programme are reported in table 2. The considered proportions take into account two parameters: an economic criterion limiting the quantity of binder used, and a mechanical one related to the unconfined compressive strength –UCS- which is function of the proportion of cement. A UCS threshold value of 1 MPa known as reference was chosen taking into account the considered valorisations for the processed product, *i.e.* a shovelable material, even a material of road sub layers. Once the implementation finished, the material is shaped in cylindrical moulds with a diameter 6 cm and height 12 cm in a manual way, in three times; with each filling the sample is packed manually by 3 successive shocks applied vertically to the ground. The storage period to room temperature is 28 days.

So, a first series referred (A), mixtures of “sediment-cement” was carried out for weighted contents of cement of 0.5, 1, 1.25 and 1.5kg for 10kg of dry sediment. Then were prepared mixtures of “sediment-cement-additives” which constituted a second series, referred (B), for which one incorporated additives (lime and fly ash) for various rates ranging between 0 and 15%.

To give an economic weighted index or note for the treatment processes is quite difficult because it depends on many not easily controllable parameters during a phase of feasibility of research works (reduced quantities to treat, non automated making process for manufacturing materials, feasibility of work…).

Nevertheless, the economic note relating to the binders can be evaluated starting from proportioning, their price and their availability on the market. A first estimate resulted in retaining the following weighting. A note of 1 was affected for the formulations containing 5% of cement, a note of 0.5 per 5% of incorporation of lime and a note of 0.1 for an addition to a total value of fly ash 5% *i.e.* of Soproline®. The quantities pressed out of dry matters and weightings (economic notes) of all the studied mixtures are gathered in table 2.

Table 2. Tested formulations with marine sediments.

Formulation	***Dry sediment***	***Cement CEM I***	***Soproline***	***Quicklime***	***Economic note***
A1	100	5	0	0	1.0
A2	100	10	0	0	2.0
A3	100	12.5	0	0	2.5
A4	100	15	0	0	3.0
B1	100	15	0	10	4.0
B2	100	10	20	10	3.4
B3	100	10	0	5	2.5
B4	100	10	20	5	2.9
B5	100	20	0	10	5.0
B6	100	15	30	10	4.6
B7	100	15	35	15	5.2
B8	100	15	0	5	3.5

Note: The numbers indicate the mass of each component in g per 100 g of dry sediment.

The different masses and percentages of each component including water for each batch were reported for each mixture and each concerned sediment. These data make it possible to obtain useful data to explain the mechanical behaviours such as the ratio water/cement (SANNIER, 2008). The percentages of water per batch are very variable, they depend on the origin of sediment and the sequence of pre-treatments applied to the latter. Let us recall that all ten sediments of the programme were not concerned with the same data processing sequences.

3. Economical discriminatory approach

The idea of this economical approach is to try to discriminate the sequence of pre-treatments or processes of treatments which make it possible at lower costs to prepare the sediments with the treatments containing hydraulic binder and to achieve the double objective of the method: solidification and stabilization of sediments. The index to measure the performance with respect to the mechanical behaviour of the solidified sediments is the unconfined compressive strength at 28 days on cylindrical samples of slenderness of 2. Stabilization is associated with the environmental behaviour evaluated starting from the tests of leaching (in solution) on monolith (NF X 31-211, 2000). The results of these tests, together with the mechanical resistances obtained, are available in literature, in particular in the series of papers dedicated to the SEDI.MAR.D. 83 project (SANNIER, 2008; BENOIT-BONNEMASON *et al*, 2009; SEBY *et al*, 2009).

Regarding all the results, we have affected an economic note to the elaborated materials or sub products obtained after hydraulic cementing with binders whatever the undergone pre-treatments (SANNIER, 2008; SANNIER *et al.*, 2008). This final note results from the sum of two notes, namely:

- a note according to the sequence of pre-treatments applied before treatment by hydraulic binder which varies from 0 (raw sediment, no treatment) to 7 (desanded, dehydrated and calcined sediment). This weighting corresponds to the addition of the note assigned individually to each process. It is established according to technical feasibility and the means necessary to its implementation (manpower, materials and consumables). This note is detailed within table 3.
- a note on the tested formulations in this programme, established starting from cement proportioning used: the higher the note is, the more important the quantity of cement and additives implemented.

Table 3. Weightings of performed treatments in the SEDI.MAR.D. 83 project.

Process	Raw (B)	Sieving	Cor. Gran.	Desanded	Dehydrated	COmposted	Phosphated	ch for liming (CH)	CAlcined	
Process note	0.0	0.5	0.5	0.5	1.0	1.5	1.5	2.0	5.5	Treatment note
B	X									0.0
DD	X			X	X					1.5
BCO	X					X				1.5
DCO	X			X		X				2.0
BCH	X							X		2.0
BCO-CG (MA)	X		X			X				2.0
DCH	X			X				X		2.5
BPCO	X					X	X			3.0
DCO-P	X			X		X	X			3.5
BPCO-CG (MA)	X		X			X	X			3.5
DPCO	X			X		X	X			3.5
BCO-PD	X	X			X	X	X			4.5
BCO-PD-CG (MA)	X	X	X		X	X	X			5.0
BCA	X	X							X	6.0
DDCA	X			X	X				X	7.0

Thus a high economic note means that the process for elaborated materials is expensive which is prejudicial within the framework of a valorisation where other materials with equivalent characteristics are on the market.

Finally the calculated notes for each treatment are gathered in table 4. They are coupled with the obtained mechanical results, namely with the value of the unconfined compressive strength obtained at 28 days (noted Rc28), and to the answer to the environmental tests defining the concept of a material which can be reused in road engineering (GTS, 2000) according to the thresholds of acceptability in covered fill (ADEME *et al*., 2006). By respecting these criteria, the sub products processed in this programme are not all acceptable for a valorisation as mentioned in the column at the right-hand side of table 4.

Table 4. Final notes d for any applied pre-treatments in the SEDI.MAR.D. 83 project.
Note: * note relative to the treatment; **note relative to the formulation with binder.

Abbreviation	Formulation	Note*	Note**	Final note	Rc_{28} (MPa)	Valorisation
B	A1	0.0	1.0	1.0	0.07	NO
B	A2	0.0	2.0	2.0	0.15	NO
B	A4	0.0	3.0	3.0	0.18	NO
BCH	A2	2.0	2.0	4.0	0.72	
BCH	A3	2.0	2.5	4.5	0.90	
BCH	A4	2.0	3.0	5.0	1.14	YES
BCO	A1	1.5	1.0	2.5	0.45	
BCO	A2	1.5	2.0	3.5	1.01	YES
BCO	A3	1.5	2.5	4.0	1.08	YES
BCO	A4	1.5	3.0	4.5	1.56	YES
BCO	A4	1.5	3.0	4.5	1.05	YES
BCO	B1	1.5	4.0	5.5	0.82	YES
BCO	B2	1.5	3.4	4.9	1.29	YES
BCO	B8	1.5	3.5	5.0	1.18	YES
BCO	B4	1.5	2.9	4.4	1.33	YES
BCO-CG (MA)	B3	2.0	2.5	4.5	3.25	YES
BCO-CG (MA)	B4	2.0	2.9	4.9	9.00	YES
DD	A1	1.5	1.0	2.5	0.35	NO
DD	A2	1.5	2.0	3.5	0.80	NO
DD	A4	1.5	3.0	4.5	1.19	NO
DCH	A2	2.5	2.0	4.5	0.57	
DCH	A3	2.5	2.5	5.0	0.70	
DCH	A4	2.5	3.0	5.5	1.30	YES
DCO	A1	2.0	1.0	3.0	0.37	NO
DCO	A2	2.0	2.0	4.0	0.71	NO
DCO	A4	2.0	3.0	5.0	1.18	
DCO	B5	2.0	5.0	7.0	1.33	YES
DCO	B6	2.0	4.6	6.6	1.39	YES
DCO	B7	2.0	5.2	7.2	1.57	YES

Table 4. (continue)

Note: * note relative to the treatment; **note relative to the formulation with binder.

Abbreviation	*Formulation*	*Note**	*Note***	*Final note*	*Rc_{28} (MPa)*	*Valorisation*
BPCO	**A1**	**3.0**	**1.0**	**4.0**	**0.37**	**NO**
BPCO	**A2**	**3.0**	**2.0**	**5.0**	**0.86**	**NO**
BPCO	**A4**	**3.0**	**3.0**	**6.0**	**1.82**	
BPCO	**A4**	**3.0**	**3.0**	**6.0**	**2.07**	**YES**
BPCO	**B1**	**3.0**	**4.0**	**7.0**	**1.61**	**YES**
BPCO	**B2**	**3.0**	**3.4**	**6.4**	**2.50**	**YES**
BPCO-CG (M.A)	**B3**	**3.5**	**2.5**	**6.0**	**8.50**	**NO**
BPCO-CG (M.A)	**B4**	**3.5**	**2.9**	**6.4**	**9.00**	**NO**
DPCO	**A4**	**3.5**	**3.0**	**6.5**	**2.01**	**YES**
DPCO	**B1**	**3.5**	**4.0**	**7.5**	**1.61**	**YES**
DPCO	**B2**	**3.5**	**3.4**	**6.9**	**2.35**	**YES**
BCA	**A1**	**6.0**	**1.0**	**7.0**	**1.37**	**YES**
BCA	**A2**	**6.0**	**2.0**	**8.0**	**2.61**	**YES**
BCA	**A4**	**6.0**	**3.0**	**9.0**	**3.74**	**YES**
DDCA	**A1**	**7.0**	**1.0**	**8.0**	**1.76**	**YES**
DDCA	**A2**	**7.0**	**2.0**	**9.0**	**2.99**	**YES**
DDCA	**A4**	**7.0**	**3.0**	**10.0**	**3.66**	**YES**
DCO-P	**B5**	**3.5**	**5.0**	**8.5**	**1.40**	**YES**
DCO-P	**B6**	**3.5**	**4.6**	**8.1**	**1.91**	**YES**
DCO-P	**B7**	**3.5**	**5.2**	**8.7**	**2.01**	**YES**
BCO-PD	**A4**	**4.5**	**3.0**	**7.5**	**0.90**	**YES**
BCO-PD	**B1**	**4.5**	**4.0**	**8.5**	**0.84**	**YES**
BCO-PD	**B2**	**4.5**	**3.4**	**7.9**	**1.22**	**YES**
BCO-PD-CG (MA)	**B3**	**5.0**	**2.5**	**7.5**	**3.75**	**YES**
BCO-PD-CG (MA)	**B4**	**5.0**	**2.9**	**7.9**	**9.50**	**YES**

The obtained values of the mechanical resistances *i.e.* unconfined compressive strengths at 28 days (Rc28) are relatively low because of the nature of stabilized materials, see table 4. Indeed, the treated sediments mainly represent fine soils with organic matters which do not present a mineral skeleton able to support high stresses in compression and where the binder is chosen to bring cohesion to this skeleton.

4. Visualization and analyzes evaluations

Once weighting or the economic note given, it is possible to show how the costs of the complete treatment evolve in relation to the selected mechanical index, *i.e.* Rc28, and this, for the different sequences of pre-treatment implemented. In other terms, we want to undertake a comparative study of the resistance values obtained at 28 days for the whole processing sequences. Table 5 recaps all the used different symbols in figures 1 and 2. Obtaining a minimal value of 1 MPa for the unconfined compressive strength constituted the target value to reach for a possible valorisation from the mechanical point of view in road engineering.

Thus, the results obtained are expressed on two figures. The first graph (figure 1.) gathers the various processes or data processing sequences implemented in which one can identify two groups with minimal resistances (n°6 group) and with maximum resistances (n°5 group).

Table 5. Used symbols for the different pre-treatments, see figures 1 and 2.

◆ B	■ BCH	○ BCO	+ BCO-CG (M.A.)	△ DD
× DCH	□ DCO	▲ BPCO	+ BPCO-CG (M.A)	◆ DPCO
○ BCA	✱ DDCA	● DCO-P	◆ BCO-PD	+ BCO-PD-CG (M.A)

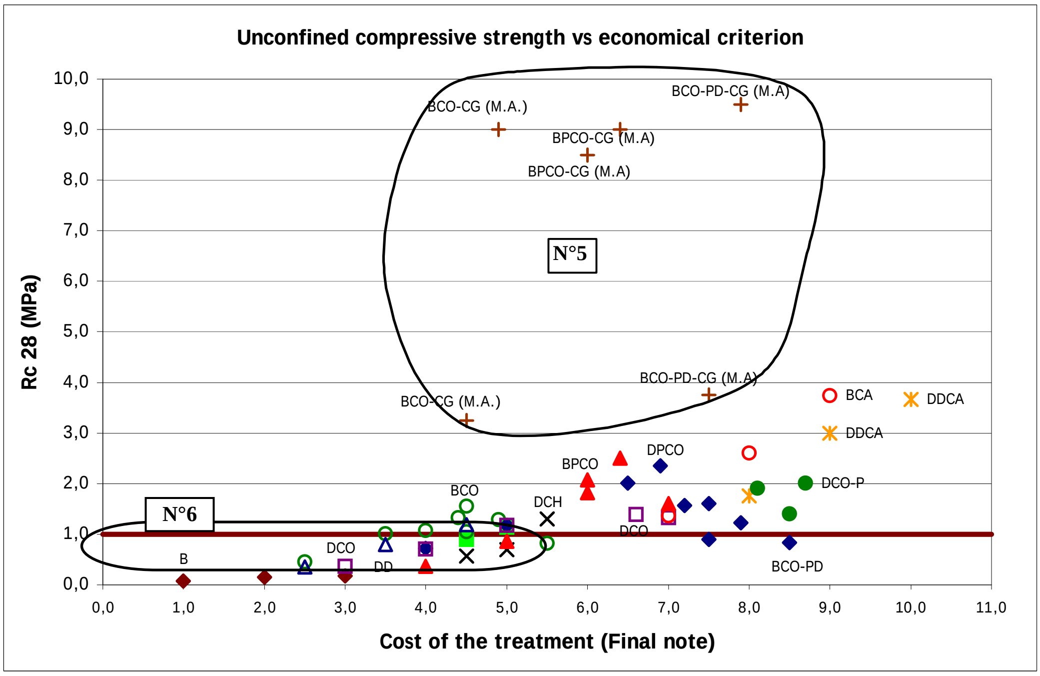

Figure 1. Relation Rc_{28} versus the complete treatment cost.

Figure 1 clearly shows the effect of the correction of granulometry which improves the granular skeleton and gives resistances definitely higher. This type of treatment corresponds to the development of a material which one can call *alternate material*. We observe that a minimum of treatment brought to the sediments, does not improve their mechanical resistance.

In figure 2, we are interested in the intermediate groups. Thus, one does not consider any more this type of *alternate material* which needs the use of aggregates from quarries. From the sustainable development point of view, it is not recommended. One holds account only of contributions out of binders themselves: cement, lime and fly ash.

The mechanical resistance values range between 1 and 4 MPa, *i.e.* above the selected threshold value.

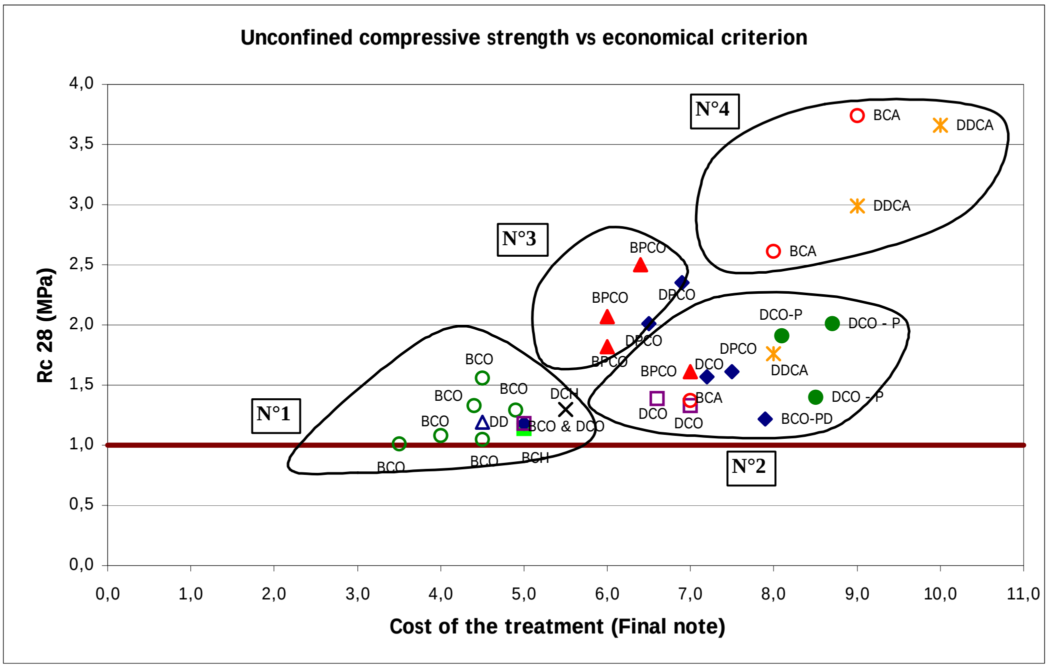

Figure 2 – Relation Rc_{28} versus the complete treatment cost
($Rc_{28} \geq 1$ MPa and without correction of granulometry).

From the evolutions observed and identified in the figures 1 and 2, we can consider six groups of sequences of pre-treatments or not with the raw sediments. Below, a description of each group is given and between brackets, is mentioned the average cost and average value of the mechanical resistance obtained:

- Group n°1 (cost = 4.6; Rc_{28} = 1.2 MPa): It includes the sediments treated by composting on the raw sediments and liming on the two grain size distributions. The process is economically low but resistances are not clearly above the threshold value. If the effect of liming is not surprising (REY, 1999), the behaviour of a composted sediment stabilized by a hydraulic binder is not or little reported in the literature. This process of pre-treatment, even if it is an economical one, requires an important surface on the ground for composting,
- Group n°2 (cost = 7.6; Rc_{28} = 1.55 MPa): It concerns the treated sediments made up of composted materials followed by a phosphatizing and of composted desanded materials. The benefit on the mechanical behaviour is very weak within sight of the expensive treatment. Phosphatizing is an industrial process already applied to the soil stabilizations and polluted mud, but also to the polluted sediments (NGUYEN, 2006) whose results are known. But there can be

an interesting combination to organize with the composting, as indicated in group 3,

- Group n°3 (cost = 6.3; Rc_{28} = 2.1 MPa): It takes into account all phosphate materials followed by a composting. One finds here a good compromise between the mechanical performance and the economic factor,
- Group n°4 (cost = 9.0; Rc_{28} = 3.3 MPa): It results from the use of a process of calcinations. The benefit on the mechanical behaviour is certainly important but it is accompanied by an expensive cost. The reuse of sediments treated by calcinations is under progress and some research works have been made (NGUYEN, 2006). The process of calcinations is often used in the case of treatment of very contaminated sediments, sometimes associated with other pre-treatments,
- Group n°5 (cost = 6.2; Rc_{28} = 7.2 MPa): It includes the whole of materials known as *alternate* ones. It seems that this mixture is most interesting. However, the only counterpart is the small quantity of treated sediment. This technique of correction of granulometry was employed for a long time in the materials for road engineering. It was recently applied in the case of fine materials such as sediments (COLIN, 2003; DUBOIS, 2006; TRAN, 2009),
- Group n°6 (cost = 4.0; Rc_{28} = 0.55 MPa): As one could expect, the samples containing the smallest percentages of cement and without additive have the lowest compressive strengths. That more particularly concerns all the raw and desanded and dehydrated sediments. These sediments are not appropriate to this type of mixture without contribution of additives.

5. Conclusions

A first analysis based on the results of an important number of tests carried out in the preliminary phase of the SEDI.MAR.D.83 programme, (SANNIER, 2008), has allowed to:

- confirm the technical feasibility of this type of treatment using hydraulic binders,
- identify the optimal percentages of cement and the possible additives, the use of which constitutes an interesting contribution to implement,
- validate the environmental feasibility compared to the possible ways of beneficial uses,
- define the suitable grain size cuttings for desanded sediments.

Following this preliminary phase, a complete test campaign of mechanical and environmental behaviour has been run out on a whole of raw or pre-treated marine sediments stabilized and/or solidified using hydraulic binders. The study, presented in this paper, was focused on the mechanical tests of behaviour while proposing the concept of a possible reused material (table 4) by introducing the idea of economic criterion which is often lacking in many research works on the valorisation of marine sediments. Thus, a methodology was implemented, which made it possible to identify the most efficient processes with a treatment by hydraulic binders.

Whatever the sequences of pre-treatment applied to the marine sediments, the treatment by binders showed that the stabilization and solidification obtained can be sufficient in the case of a valorisation such as material for road and earthworks engineering (road sub layers and covered landfills). Indeed, the values of compressive strength are sufficient and the results of the environmental tests compared with the thresholds of acceptability fixed by the guide of the ministry for Equipment (ADEME *et al*., 2006) prove to be satisfactory (BENOIT-BONNEMASON *et al*, 2009; SANNIER, 2008; SEBY *et al*, 2009).

This economic and simple approach made it possible to identify groups of treatments with equivalent performances associating the concept of cost, mechanical resistance and reused product. The main results of this study concern:

- The process of treatment by phosphatizing accompanied by composting brings the best compromise resistance/cost for a treatment with the hydraulic binder. This corresponds to group 3.
- The incorporation of additives with lower costs as the fly-ashes *i.e.* Soproline® or quicklime can prove to be interesting, in particular in substitution for cement. Moreover, these additives exploit a part of the water content, the content of organic matters, on long-term resistance. The pozzolanic effect is not considered here because tests beyond 28 days are necessary (LEVACHER *et al.*, 2008, SILITONGA *et al.*, 2009). With these additives, the sequences of pre-treatment can be reduced.
- An alternative solution with the treatments by phosphatizing and/or calcinations which remain very expensive is based on the use of a method of treatment with correction of granulometry. Of course, that passes by the valorisation of smaller volumes of sediments (proportioning to small percentages of marine sediments) by adding a quarry material or equivalent. Indeed, from its contribution of coarser elements, it reduces the concentrations in inhibiting agents for the solidification of the binder and increases the cohesion of the mineral skeleton.

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