Marine Dredging Sediments Valorization in Self-Compacting Concretes

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Abstract

Rock and eroded soil are transported by wind, tide, and human action (development works), and deposited as sediment in ports, estuaries, and rivers. The sediment accumulation at the bottom of ports disrupts maritime activities and disturbs the physicochemical balance of water bodies. As a result, dredging is necessary to reduce sediment deposits and restore the natural environment for proper port functioning. At the national level, the maintenance of the 6,500-kilometer French coastline would require the extraction of about fifty million cubic meters of marine sediment every year. These dredged sediments have been used in civil engineering applications for about ten years, in order to reduce their economic and environmental impact. The proposed study addresses the potential use of sediments to produce accropode blocks for maritime public works applications. It consists in developing concrete mixtures using dredged marine sediment treated to protect against erosion. A study of material characterization, optimization of the composition of the concrete formulation, as well as a determination of the mechanical, physical and durability properties of the concrete were necessary to validate the technical feasibility of this new solution. Around 700 small accropode blocks were then prepared to better analyze the structure stability against swell effects. The obtained results show that the sediments could not produce Self Compacting Concrete (SCC). However, sediment treatment with 6% by weight of cement has enabled the production of SCC. It is worth noting that the use of superplasticizer was essential to ensure concrete workability. Increasing the cement percentage has also improved the composite workability. Finally, a concrete compressive strength greater than 40 MPa has been achieved when using 300 kg/m^3 of treated sediments.

Keywords: Circular economy; Dredged sediments; Workability; Concrete; Valorization

1. Introduction

Materials that are produced as a result of rock and soil erosion are transported by climatic actions (wind, tides) and human actions (development works) and deposited as sediment in ports, estuaries, and rivers. Sediment accumulation at the bottom of ports disrupts maritime activities and disturbs the physicochemical balance of water bodies. As a result, dredging is a necessary to reduce sediment deposits to restore the natural environment for proper port functioning. At the national level, the maintenance of the 6,500 kilometers of French coastline would require the extraction of about 50 million m^3 of marine sediments every year.

Even though considered as waste, these sediments have been used in civil engineering applications for several years. They have been used in road construction (Miraoui et al., 2012), brick manufacture (Achour et al., 2019), mortar and concrete production (Benzerzour et al., 2018), and cement production (Amar et al., 2018). Use of dredged sediments as a substitute for traditional aggregates could provide a number of advantages: improved management of dredged sediments, efficiency/ease of access to resources at site of use, and prevention of harm caused by the resource as it is used in its original environment.

This study explores the potential use of these sediments in the manufacture of accropode blocks for the protection of the coastline against the effects of swells (Figure 1). It consists of developing concrete mixes using marine dredged sediments that required sediment treatment, material characterization, concrete composition and formulation, and determination of concrete mechanical, physical, and durability properties. Around 700 small accropode blocks were then prepared to better analyze the structure stability against swell effects. The obtained results show that the raw sediments could not produce Self Compacting Concrete (SCC). However, sediment treated with 6% by dry weight of cement has enabled the production of SCC. It is worth noting that the use of superplasticizer was essential to ensure concrete workability. Increasing the cement percentage has also improved the composite workability. Finally, a concrete compressive strength larger than 40 MPa has been achieved when using 300 kg/m^3 of sediment.

2. Experimental Program

2.1. Materials

The cement used for this study is ordinary Portland cement CEM I 52.5R. Limestone fillers were used to improve the workability of self-compacting concrete by improving particle size distribution and to increaseconcrete strength of concrete especially at a young age. The limestone fillers were supplied by the Aucais factory (Urville – 14). They came in the form of an odorless powder with a light ochre color.

Three types of aggregates were used, namely 0/4 mm sand, 2/6 mm gravel, and 6/10 mm gravel. The particle size distribution is given in Figure 1 and the different characteristics of the aggregates used are given in Table 1 and Figure 1. The aggregates were dried in an oven at 105 ° C to a constant mass. Two concrete additives were used in the concrete mixtures. The first one was a superplasticizer, which was used to improve the fluidity of the mixture and act on the de-flocculation of the cement grains but also of all the fines present in the concrete. The second one was a hardening accelerator, which was added to reduce the setting time of cement due to sediments, and also to increase concrete early age strength.

Table 1: Aggregate physical properties

Physical Properties	Standard	S 0/4 mm	G 2/6 mm	G 6/10 mm
Actual density (kg/m^3)	NF EN 1097-6	2620	2571	2596
Bulk density (kg/m^3)	NF EN 1097-6	1469	1343	1357
Compacted bulk density (kg/m^3)	LCP method	1790	1473	1476

Bulk compactness	NF EN 1097-3	0.561	0.522	0.523
Compactness measured by shaking table	LCP method	0.683	0.573	0.569
Sand equivalent	NF EN 933-8	82.1	-	-
Water absorption coefficient (%)	NF EN 1097-6	0.40	1.22	0.70

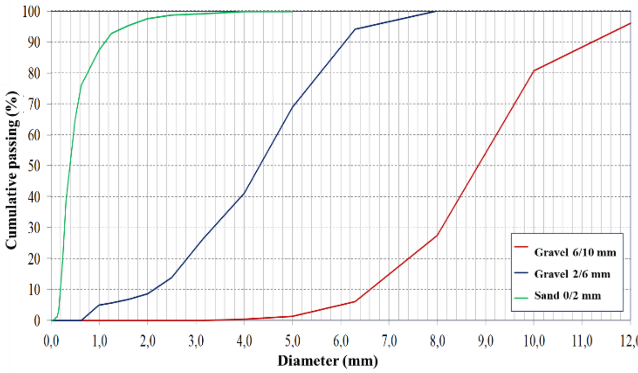

Fig. 1: Aggregate particle size distribution

The sediments were wet and stored in 100 L buckets. Table 2 summarizes the sediment density, organic matter content, particle size distribution and Atterberg limits..خطأ! لم يتم العثور على مصدر المرجع.

Table 2: Dredged sediment physical properties

Physical properties		**Values**
Density (kg/m³)		2545
Organic matter content (%)		7.02
Particle size distribution	D_{10} (µm)	5.4
	D_{50} (µm)	51.4
	D_{90} (µm)	235.3
	Average size (µm)	94.1
Atterberg limits	Liquidity limit w_L (%)	86.8
	Plasticity limit w_P (%)	40.4
	Plasticity index I_p	46.4

2.2. Dredged sediment treatment

To obtain a self-compacting concrete, the dredged sediments were treated with cement to reduce their shortcomings such as high water absorption, cohesion, and organic matter content as well as large specific surface area. The dredged sediments were treated as follows:

- Dried to a constant mass.
- Crushed to a fine powder.
- Dry-mixed using CEM cement I 52.5 R. 6% is the cement rate used for sediment treatment.
- Added water very slowly in the mixer while rotating. The amount of added water should be 25 to 28% of the dredged sediment mass. Water is added as slowly as possible, even by spraying, to obtain a porous and powdery mix.
- Dried the mix in an oven at 40°C to speed up drying.

The treated sediments included 74.1% of dredged sediment, 4.4% of cement, and 21.5% of water: 21.5%. These values make it possible to calculate the amount of treated sediment to be added to concrete using the amount of raw sediment.

2.3. Concrete preparation and specimen casting

100-liter concrete batches were prepared. The fresh properties were tested immediately after six minutes of mixing. After that, the molds were filled and vibrated for 5 minutes. All the molds were covered with plastic sheets and stored for 24 hours in the laboratory prior to demoulding. Then, they were cured at 20^0C and relative humidity (RH) of 80–95% until testing.

3. Testing Program

3.1. Fresh properties

The slump was measured using Abram's cone after each concrete batch according to EN 12350-8. Fresh mix percent entrapped air was measured using an 8L pressure gauge meter according to EN 12350-7 standard. The density was determined by measuring the mass and volume of the vibrated molds according to the NF EN 12350-6 and NF EN 12350-10.

3.2. Mechanical properties

Concrete compressive strengths were measured according to EN 12390-3. On the other hand, dry bulk densities were computed according to NF P18-459. Both tests were performed on hardened 100x200mm concrete cylinders.

3.3. Durability properties

The Water Accessible Porosity (WAP) of hardened concrete specimens was measured using vacuum saturation and hydrostatic balance according to NF P18-459 standard after curing periods of 28 and 90 days. For each concrete mix, two 100x200mm concrete cylinders were removed the 20-mm upper and lower portions and then sliced in three identical portions. The saturated surface dry state (SSD) of the specimens was obtained using vacuum saturation. Initially, the specimens were placed in a vacuum chamber with silica gel to decrease the contact angle of the water and dry pores in the specimens. The water was introduced in the chamber after 4 hours to immerse the specimens and the vacuum was kept on for an additional 44 hours. The WAP was obtained from the mass of SSD specimens measured in air and in water, and that of oven dried at 105 C specimens.

3.4. Formulation and Implementation of Cementitious Composite with and without Dredged Sediments

- **Control Concrete Mix Designs (without sediments)**

Table Three control concrete mixes were designed (BT1, BT2 and BT3). The aggregate quantities for the control concretes were computed based on the granular stacking (MEG) method. A mix design with maximum compactness was retained for the control concretes, namely, 45% of sand, 18% of gravel#1, and 37% of gravel#2. Table 3 summaries the control concrete mix designs. Table 4 summarizes the concrete properties in the fresh and hardened states.

Table 3: Control concrete design mixes (without sediment)

Mixtures	**BT1**	**BT2**	**BT3**
Cement (kg/m^3)	338	361	368
Limestone filler	113	120	123
Equivalent binder	365	391	399
Efficient water	152	162	147
Gravel 2/6 mm	329	319	325
Gravel 6/10 mm	675	655	668
Sand 0/4 mm	821	797	812

Superplasticizer concrete additive (kg/m^3)	5.4	5.8	5.9
Setting accelerator concrete additive (kg/m^3)	7.8	8.3	8.5
Effective E/C ratio	0.45	0.45	0.40

Table 4 shows that BT3 concrete exhibited increased performance. Thus, BT3 was chosen as the reference for the composition of sediment concrete with and without treatment.

Table 4: Control concrete mechanical properties

State	Physical properties		BT1	BT2	BT3
Fresh condition	Air content (%)		3.8	3.3	3.5
	Abrams cone spread (cm)		71.0	70.0	67.5
	Waiting time 50cm spreading (s)		5.5	6.5	5.0
	Box L	Ratio H_1/H_2	0.91	0.90	0.90
		Time T_1 (s)	5.1	1.5	1.5
		Time T_2 (s)	6.9	2.5	4.8
	Fresh density (kg/m^3)		2387	2409	2397
Hardened state	Compressive strength at 28 days (MPa)		53.8	59.6	74.3
	28-day tensile strength (MPa)		4.7	4.9	5.3
	Dry bulk density (kg/m^3)		2282	2307	2292
	Porosity accessible to water (%)		12.4	11.9	11,5
	Static Elastic Modulus (GPa)		41.0	41.9	43.4
	Dynamic Elastic Modulus (GPa)		44.3	44.2	44.8
	Total Shrinkage at 90 days (µm/m)		288	298	288
	Total mass loss after 90 days of drying (%)		0.95	0.85	0.63

- **Dredged Sediment Based Concrete Mix Designs**

Several wastes were tested to achieve the performance of a self-compacting concrete having a 28-day compressive strength greater than 40 MPa. Two design approaches were implemented. The sand was substituted with dredged sediment in the first approach. On the other hand, limestone filler was totally replaced with the dredged sediments.

First approach: 30% by weight of the sand was replaced by dredged sediments. Table 5 summarizes the mix design of sediment-based concrete batches, which were named BS (Sediment Concrete).

Table 5: First approach concrete design mixes

Parameters	BS1*
Cement (kg/m^3)	368
Limestone filler (kg/m^3)	123
Equivalent binder (kg/m^3)	399
Effective water (kg/m^3)	222
Gravel 2/6 mm (kg/m^3)	325
Gravel 6/10 mm (kg/m^3)	668
Sand 0/4 mm (kg/m^3)	568
Superplasticizer concrete additive (kg/m^3)	14.7
Setting accelerator concrete additive (kg/m^3)	8.5
Sediment noise (kg/m^3)	244
Effective E/C ratio	0.65

* BS1: concrete with 30% sediment.

The workability of BS1 concrete did not have self-compacting properties even with E/C ratio = 0.65 and 4.0% of the superplasticizer. For these reasons, BS1 concrete was excluded from this study.

Second approach: The grain size of the sediment particles is almost equivalent to limestone filler. Therefore, limestone fillers were substituted by dry raw sediment (a substitution of 100% mass). The superplasticizer additive concrete was used instead of setting accelerator concrete additive for a better performance in the de-flocculation of cementitious particles. Tables 6 and 7 summarize the composition and the properties of the second approach concrete design mixes, respectively.

Table 6: Concrete formulation according to Approach 2

Composition (kg/m^3)	**BS2**
Cement	368
Equivalent binder	368
Efficient water	209
Gravel 2/6 mm	325
Gravel 6/10 mm	668
Sand 0/2 mm	812
Superplasticizer concrete additive	11.3
Setting accelerator concrete additive	8.5
Raw sediments	123
Effective E/C ratio	0.58

Table 7: Concrete characteristic where sediment replaces limestone filler

BS2	
Characteristics	Value
Occluded air content (%)	6.5
Abrams cone subsidence (cm)	9.3
Fresh density (kg/m^3)	2234
Compressive strength at 28 days (MPa)	39.2
28-day tensile strength (MPa)	3.5
Shrinkage at 90 days (µm/m)	616
Total mass loss after 90 days of drying (%)	1.24

In the two approaches, the cement treatment was necessary for achieving self-compacting workability.

- **Cement-treated sediment-based concrete mix**

In this part of the study, the concrete mix included a partial replacement by mass (5, 10, 15 and 20%) of fine and coarse aggregates with treated sediments. The amount of binder was increased by 20% to improve the workability of concrete mix. Table 8 summarizes the treated sediment-based concrete mixes. On the other hand, Table 9 summarizes the main characteristics of these concrete mixes.

Table 8: Concretes mixes with treated sediments partially replacing aggregates

Composition	**BS3 –** 5.0%		**BS4 –** 10.0%		**BS5 –** 15.0%		**BS6 –** 20.0%	
	F.I	F.F.	F.I	F.F.	F.I	F.F.	F.I	F.F.
Cement (kg/m^3)	407	373	447	381	540	423	590	441
Limestone filler (kg/m^3)	136	124	149	127	180	141	197	147
Equivalent binder (kg/m^3)	441	404	484	413	585	549	639	478
Effective water (kg/m^3)	186	170	246	210	297	233	325	242
Gravel 2/6 mm (kg/m^3)	309	283	292	249	276	216	260	194
Gravel 6/10 mm (kg/m^3)	634	581	601	512	576	451	534	399
Sand 0/4 mm (kg/m^3)	771	706	730	623	689	541	649	485
Superplasticizer 1(kg/m^3)	6.5	6.0	7.2	6.1	8.6	6.8	9.4	7.1
Superplasticizer 2 (kg/m^3)	8.1	7.5	8.9	7.6	10.8	8.5	11.8	8.8
Raw sediment (treated) (kg/m^3)	90	83	180	154	271	212	361	270

Raw sediment/aggregates (%)	5.0	10.0	15.0	20.0
Treated sediment/BT3 aggregates (%)	6.8	13.5	20.3	27.0
Effective W/C ratio	0.46	0.55	0.55	0.55

Table 9: Characteristics of concrete mixes with treated sediments partially replacing aggregates

State	Characteristics		**BT3 –** 0.0%	**BS3 –** 5.0%	**BS4 –** 10.0%	**BS5 –** 15.0%	**BS6 –** 20.0%
Fresh condition	Occluded air content (%)		3.5	3.6	3.0	3.2	4.2
	Abrams cone spread (cm)		67.5	81	68	71	65
	Time for 50cm spreading (s)		5.5	0.88	1.98	1.53	2.09
	Box L	Ratio H_1/H_2	0.90	0.91	0.87	0.91	0.91
		Time T_1	1.5	0.8	1.1	0.8	1.1
		Time T_2	4.8	1.9	2.0	1.9	2.0
	Fresh density (kg/m^3)		2397	2324	2261	2222	2182
Hardened State – Physics and Mechanics	Compressive strength at 28 days (MPa)		74.3	59.7	50.5	45.9	44.6
	28-day tensile strength (MPa)		5.30	4.09	3.78	3.59	3.40
	Dry bulk density (kg/m^3)		2292	2222	2147	2088	2052
	Porosity accessible to water (%)		11.5	14.6	16.6	19.3	20.3
	Static Elastic Modulus (GPa)		43.4	36.3	30.3	26.7	22.6
	Dynamic Elastic Modulus (GPa)		44.8	39.7	35.3	31.7	30.4
	Shrinkage at 90 days (µm/m)		288	468	656	834	966
	Total mass loss drying (%)		0.64	1.01	1.34	1.74	1.74

We can conclude that treated sediment-based concretes meet the specifications initially planned. The compressive strength of all these concretes is greater than 40 MPa and the spreading of these concretes is greater than 60 cm. The flow time at t_{50} and the filling ratio H1/H2 are also satisfactory. The BS3, BS4, BS5 and BS6 concretes meet the requirements of self-compacting concretes.

4. Conclusion

The study addressed the potential use of dredged sediments to produce accropode blocks for maritime public works applications. Concrete mixes were developed using dredged sediments that required treatment, material characterization, concrete composition and formulation, and determination of concrete mechanical, physical, and durability properties.

The study has the following conclusions:

- The dredged sediment is not favorable for obtaining a self-compacting concrete,
- The treatment of sediments with cement at 6% by weight achieves a self-compacting concrete,
- To ensure the workability of concrete, the use of concrete additive, such as superplasticizer, is essential,
- Increasing the quantities of cement in concrete mix improves the workability of the composite,
- Using 300 kg/m^3 of sediment allows the concrete to reach a compressive strength greater than 40 MPa.

The obtained results of this study show the feasibility of using sediments in the formulations of self-compacting concretes (SCC). Nevertheless, this study should be complemented by an estimate of the economic impact as well as a life-cycle analysis in order to develop on an industrial scale this new sector for the recovery of dredging sediments.

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