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1 **Valorization of uncontaminated dredged marine sediment through sand substitution in**
2 **marine grade concrete**

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16 **Highlights**

- 17 • Untreated fine sediments can be used as a substitute for sand in XS2 concrete
18 • Untreated fine marine sediments have a negative effect on concrete properties
19 • Up to 10% of sediment content resulted in comparable concrete properties
20 • Up to 30% of sediment content can be used after optimizing the concrete mix design

21 **Abstract**

22 Marine sediment disposal is an important economic and environmental issue worldwide. In
23 order to minimize these discharges and optimize resources through a circular economy
24 approach, this study discusses the potential use of fine marine sediments without treatments as
25 a sand substitute in the marine concrete class (XS2, C30/37). The Dreux-Gorisse method was
26 applied to find the concrete formulation containing 10, 20, 30, 40 and 50% sediment by weight.
27 The results show that an XS2 concrete C30/37 with a water to binder ratio of 0.55 could be

28 designed with 10% of sediment replacement content without significantly affecting the concrete
29 properties. However, the optimization of concrete mix design shows that marine concrete (XS2,
30 C30/37) could be designed with 30% of sediment replacement content without significantly
31 affecting the potential durability and the estimated lifetime of the concrete structure.

32 **Keywords:** dredged marine sediments, valorization, sand substitution, marine concrete,
33 concrete properties, potential durability, estimated lifetime

34 **1. Introduction**

35 Concrete is the most widely used material in the world after water [1]. It is mainly composed
36 of gravel, sand, binder and water [2]. Today, the large consumption of concrete is accompanied
37 by rapid consumption of natural resources, and by a stricter requirement of environmental
38 protocols. Therefore, making concrete in an environmentally friendly manner using alternative
39 materials in the concrete manufacturing process becomes vitally important [3].

40 The production of one ton of Portland cement (CEM I) releases approximately one ton of carbon
41 dioxide (CO₂). This energy-intensive production process involves significant resource
42 consumption [4]. Therefore, several studies were carried out to find substitute materials that
43 can be used as a partial replacement for CEM I. Then, the main identified supplementary
44 cementitious materials (SCM) are ground granulated blast furnace slag (GGBS), fly ash, silica
45 fume, metakaolin, and more recently marine sediments (treated in most cases) [5–10]. In recent
46 years, the valorization of marine sediments as SCM in the production of concrete and self-
47 compacting concrete has been widely studied [8,11–13]. For example, Safhi *et al.* showed that
48 the use of 10% of treated marine sediment (dredged from Dunkirk harbor) as SCM in self-
49 compacting concrete has no significant effect on fresh properties (workability and flowability)
50 and the durability performance (chloride penetrability and external sulfate attack) of concrete
51 specimens [11,14].

52 In addition to cement, the concrete industry uses a large amount of sand. Sand is the fine
53 aggregate used in concrete manufacturing to ensure the granular continuity between the coarse
54 aggregate and the cement [15]. Sand is generally obtained by extraction from land quarries or
55 riverbeds. Because of the regulations and/or limited availability, the river deposit resources are
56 becoming rare and expensive in some areas. On the other hand, crushing rocks to obtain the
57 sandy fraction is difficult and requires high energy consumption [2]. In addition, sand is
58 becoming scarce in some regions of the earth, and in some cases, the sand should be transported
59 over long distances, which imposes negative economic and environmental impacts [16]. In

60 contrast to the extensive SCM research, there is relatively limited experimental research on the
61 feasibility of replacing crushed sand (CS) with an alternative material in concrete production.
62 To date, two candidate materials have been mainly presented in the literature: dune sand and
63 dredged marine sediments (DMS).

64 Dune sand (desert sand) could serve as an abundant alternative sand source in many countries.
65 It is available from many sources around the world. The dune sand is composed of fine particles
66 with spherical shapes and a finesse modulus (FM) close to 1. Research experiments show that
67 dune sand can be used as a partial substitute for crushed sand in properly designed concrete
68 mixes, without adverse effects [17–19].

69 Unlike the dune sand, the use of DMS as a partial replacement of CS in concrete production
70 seems to be more complicated and difficult [20]. The rare research on the use of DMS as a
71 partial substitution of CS in concrete or mortar manufacturing has shown mixed results.
72 Elmoueden *et al.* studied the influence of partial substitution of sand by 15, 30 and 50% of
73 dredged sediments in the production of air foam concretes. They found that sand replacement
74 causes an increase in the compressive strength and density of concrete specimens [21]. Moradi
75 and Shahnoori studied the effects of replacing sand with 15, 25, 35, 50 and 100% of DMS
76 (dredged from the Persian Gulf) in the production of roller-compacted concrete. They found
77 that the replacement of sand by DMS at a percentage smaller than 25% increases the
78 compressive strength and decreases the water absorption and water permeability of concrete
79 specimens. Contrariwise, high DMS percentage (>35%) decreases the mechanical properties of
80 concrete specimens [22]. Ben Allal *et al.* showed that the use of 20% of raw sediments
81 (collected from the ports of Tangier and Larache, Morocco) as a sand replacement leads to a
82 30% decrease in the compressive strength of mortar specimens [23]. However, for the proper
83 use of DMS as a substitute for sand in concrete production, treatment is required [20]. In fact,
84 DMS is mainly composed of water, fine particles, organic pollutants (tributyltin,
85 polychlorinated biphenyls, polycyclic aromatic hydrocarbons...), inorganic pollutants (heavy
86 metals: mercury, cadmium, arsenic, chromium...) and salts [6,10,20,24]. It is shown that the
87 salts and the pollutants can affect the characteristics and the properties (cement hydration
88 reaction, structural strength progress...) of concrete made with DMS [25].

89 Accordingly, to benefit from the large volume of marine sediments dredged annually (300
90 million m³ for the whole of Europe and 300 million m³ in the USA) [7], further research and
91 studies are needed on the partial replacement of CS with dominantly fine-grained DMS. To the
92 best of our knowledge, no information regarding the use of DMS as a partial substitute for CS

93 in the manufacturing of marine concrete (XS2 environmental exposure conditions as defined in
94 European Standard NF EN 206-1) [26] has been published. Therefore, the objective of this
95 present study is to identify the possibility of using fine-grained dominated DMS as a CS
96 substitute in marine concrete and to optimize the formulation, without engaging in polluting
97 and expensive treatment processes. The long-term objective is to promote a circular economy
98 approach by using fine untreated marine sediment (landfilled in most cases) as a partial
99 replacement for sand in the production of concrete materials.

100 **2. Materials and Methods**

101 **2.1. Experimental plan**

102 In order to achieve the aims of this study, the procedure was planned in four main stages. 1)
103 Physio-chemical characterization of DMS 2) Preparation of concrete specimens (water to
104 binder ratio of 0.55) with 10, 20, 30, 40 and 50% of DMS as CS substitution, 3) Selection of
105 substitution percentage, 4) optimization of the concrete formulation (Table 7).

106 The targeted concrete is a marine concrete (XS2) with a minimum compressive strength of 38
107 MPa (at 28 days, C30/37) and a slump of 190 mm \pm 25 mm which gives a plastic concrete of
108 class S4. According to NF EN 206-1, this concrete must be manufactured with water to binder
109 ratio (w/b) of a maximum of 0.55.

110 In this paper, the Dreux-Gorisse method was applied to find the concrete formulation [27] and
111 the obtained concrete was evaluated based on its workability, water porosity (water penetration
112 under pressure), water absorption and compressive strength.

113 The substitution percentage selected in stage 3 is the highest percentage which:

- 114 • Requires no more than 2% of superplasticizer to achieve 180 mm \pm 25 mm with slump
115 test
- 116 • Gives a mechanical compressive resistance greater than 38 MPa at 28 days
- 117 • Does not significantly affect the water porosity (chosen as an indicator to assess the
118 general quality of concrete)

119 The optimization of the concrete mix design was performed by adjusting the following
120 parameters (Table 7):

- 121 • The quantity of mixing water (specimens with a w/b ratio of 0.55 and with an excess
122 water of 10 L/m³ and 20 L/m³)

- 123 • The superplasticizer (SP2)
- 124 • The granular arrangement, by using a gravel 4/6.3 (g 4/6.3)
- 125 • The water to binder ratio ($w/b = 0.50$, $w/b = 0.45$)

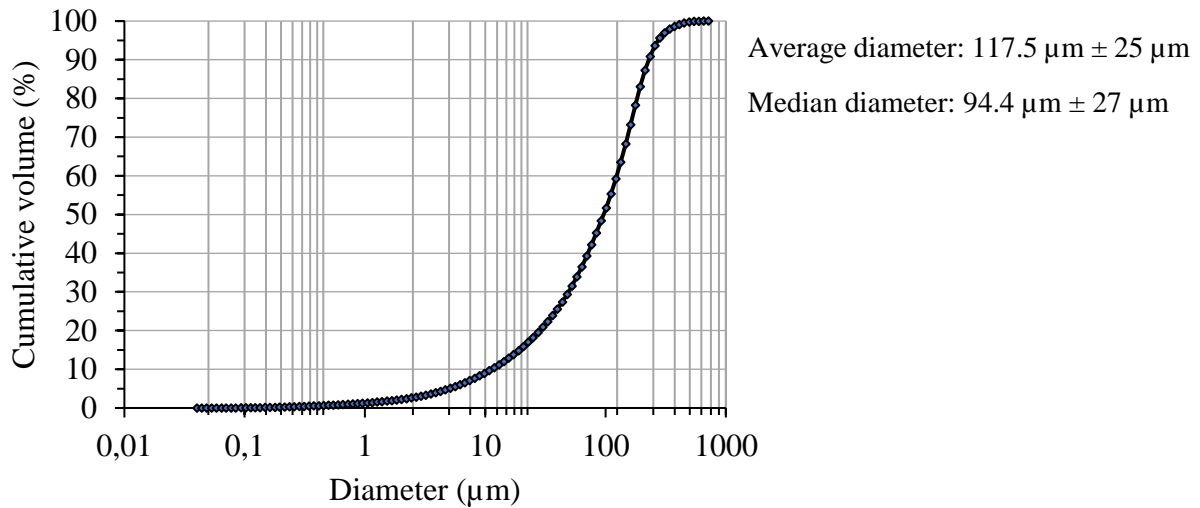
126 2.2. Physio-chemical characterization of DMS

127 The DMS used in this study was obtained from Port-Camargue (Grau du Roi, France). The
128 geographic locations of the dredging operation are shown in Figure 1. The dredged sediments
129 from all the locations were mixed. The expected fraction of sediment was separated based on
130 particle weight using hydrocyclone and dewatered by geotubes. Then, the collected samples
131 from the geotubes were kept in hermetically sealed plastic bags and stored in the laboratory at
132 20°C until use. This sediment was not contaminated by heavy metals, polycyclic aromatic
133 hydrocarbons, and Polychlorinated biphenyls (data not shown).



134
135 *Figure 1. Geographic locations of dredging operation at port-Camargue (France) [28].*

136 The particle size distribution of the DMS samples was determined using laser diffraction
137 particle size analyzer (Beckman Coulter S13320) (Figure 2). The results show that the DMS
138 has a mean and median diameter of 117.5 μm and 94.4 μm respectively. According to ISO
139 13320, this DMS contains 2.2% clay fraction ($d < 2 \mu\text{m}$), 36.3% fine fraction ($2 \mu\text{m} < d < 63$
140 μm), 48.7% fine sand ($63 \mu\text{m} < d < 200 \mu\text{m}$) and 12.8% sand ($200 \mu\text{m} < d < 2000 \mu\text{m}$).



141

142 *Figure 2. Particle size distribution of DMS used in this study. The results were obtained using laser particle size analysis*
 143 *according to ISO 13320.*

144 The physical, mineralogical, and chemical characteristics of DMS used in this study are
 145 summarized in table 1. All experiments were performed in triplicate.

146 *Table 1. Physical and mineralogical characteristics of DMS used in this study.*

| Material characteristic | Standard used | Measuring tool | DMS |
|---|-----------------|--|--|
| Water content | NF P94-050 | Oven at 105°C | 17.7 ± 5.6 |
| pH | | pH meter | 8.67 ± 0.13 |
| Density (g/cm ³) | NF EN 1097-7 | Micrometrics AccuPyc 1330 helium pycnometer | 2.66 ± 0.01 |
| Specific surface area (cm ² /g) | NF EN ISO 18757 | Multipoint BET (Brunauer-Emmett- Teller) N2 adsorption | 3.14 ± 0.82 |
| Total organic carbon (%) | NF EN 13137 | TOC-meter (Vario TOC cube) | 2.69 ± 0.26 |
| Blue methylene value (g/100g) | NF P94-068 | Methylene blue solution | 0.81 ± 0.45 |
| Calcite (%) | | Thermogravimetric analysis | 10.8 ± 0.52 |
| Major mineral elements (X-ray diffraction analysis) | | D8 Advance diffractometer (Bruker) | Calcite (CaCO ₃), Quartz (SiO ₂) and Anhydrite (CaSO ₄) |
| Morphology | | Scanning electron microscopy (SEM) | Angular shape |

| | | | |
|------------------------------------|-----------|--------------------|-------------------------------------|
| Chemical composition (%) | DIN 51001 | X-ray fluorescence | 52.85 SiO ₂ |
| | | | 9.56 Al ₂ O ₃ |
| | | | 3.15 Fe ₂ O ₃ |
| | | | 0.37 TiO ₂ |
| | | | 3.30 K ₂ O |
| | | | 1.48 Na ₂ O |
| | | | 13.25 CaO |
| | | | 1.40 MgO |
| | | | 0.00 PbO |
| | | | 0.03 BaO |
| | | | 0.92 SO ₃ |
| | | | 0.07 MnO |
| 0.10 P ₂ O ₅ | | | |
| 0.01 ZrO ₂ | | | |
| | | Ion chromatography | 0.67 Cl ⁻ |

147

148 2.3. Materials used in the preparation of concrete specimens

149 2.3.1. Blended cement

150 In order to reduce the carbon footprint of concrete and to improve its durability in the marine
 151 environment [29,30], the blended cement used in this study is composed of 70% Portland
 152 cement 52.5 N and 30% Ground Granulated Blast-furnace Slag (Ecocem, France). It has been
 153 shown that the use of GGBS increases the durability of concrete against external aggression,
 154 including chloride penetration [31]. As specified in its technical data sheet, the reactivity index
 155 of this GGBS is 0.9. Its chemical composition is mentioned in table 2.

156 *Table 2. Chemical composition (%) of Ground Granulated Blast-furnace Slag used in this study.*

| SiO ₂ | Al ₂ O ₃ | Fe ₂ O ₃ | CaO | MgO | TiO ₂ | SO ₃ | Cl ⁻ | S ²⁻ | Na ₂ O | K ₂ O |
|------------------|--------------------------------|--------------------------------|------|-----|------------------|-----------------|-----------------|-----------------|-------------------|------------------|
| 35.1 | 11.1 | 0.4 | 42.1 | 7.0 | 0.8 | 0.1 | 0.03 | 0.6 | 0.21 | 0.43 |

157 The cement used in this study, Portland cement 52,5 N - SR 5 CE PM-CP2 NF HTS
 158 (DURABAT[®] X-TREM) is specially formulated to resist sulfate and seawater (chloride) as
 159 stipulated in the technical data sheet. The characteristics of this cement are summarized in table
 160 3.

161 *Table 3 ; Characteristics of Portland cement 52,5 N used in this study. Min: Minute.*

| MgO | C3S | C2S | C3A | C4AF | Secondary constituents | Setting start time | Average of compressive strength at 28 days | True density |
|------|-----|-----|-----|------|------------------------|--------------------|--|------------------------|
| 0.7% | 66% | 19% | 4% | 7% | 3% | 180 min | 67 MPa | 3.18 g/cm ³ |

162

163 2.3.2. Gravel

164 In this study, two types of crushed limestone were used, supplied by Languedoc Roussillon
165 Matériaux (LRM). The grain size distributions of these gravel are shown in Figure 3. Gravel
166 with size ranged from 6.3 to 14 mm (G) was used as coarse aggregate in all concrete specimens
167 while gravel with size ranged from 4 to 6.3 mm (g) was used only during the third stage of the
168 experimental plan (concrete formulation optimization). The characteristics of these two types
169 of gravel are presented in Table 4.

170 *Table 4. Characteristics of gravel used in this study.*

| Type | True density (Mg/m ³) | Water absorption (%) | Acid soluble sulfate (%) | Chloride (%) |
|---------------|--------------------------------------|-------------------------|-----------------------------|--------------|
| Gravel 4-6.3 | 2.66 | 0.9 | 0.011 | < 0.001 |
| Gravel 6.3-14 | 2.63 | 0.7 | 0.05 | < 0.001 |

171

172 2.3.3. Adjuvant and Superplasticizer

173 Two types of commercial superplasticizers (SP1 and SP2) were used in this study (Table 1).
174 SP1 as the main SP applied in this study, is a new generation of superplasticizers based on a
175 new technology of polymer synthesis. According to its technical data sheet, this SP maintains
176 the workability of concretes for a long time without delaying the compressive strength
177 development.

178 SP2 has been used to optimize the concrete formulation. It is recommended when CEM III is
179 used in concrete manufacturing. This SP is compliant with concrete intended for contact with
180 potable water (18 CLP LY 036).

181 *Table 5. Properties of superplasticizers and adjuvant used in this study.*

| | Chemical composition | Density (g/cm ³) | Solid content (% wt) |
|--------------------|----------------------|------------------------------|----------------------|
| Superplasticizer 1 | Polycarboxylate | 1.10 | 35.00 |
| Superplasticizer 2 | Polycarboxylate | 1.07 | 31.00 |

182

183 2.3.4. Sand and sand-DMS mixes

184 The sand used in this study is calcareous crushed sand with sizes ranging from 0 to 4 mm
185 (LRM). The sand-DMS mixes were obtained as follows:

186 1- Ambient Air drying of DMS for 48 hours: The water content decreases from 17.7 to 8%
187 approximately

188 2- Mixing of DMS and CS according to the mass percentage (10, 20, 30, 40 or 50%) using a
 189 laboratory mortar mixer

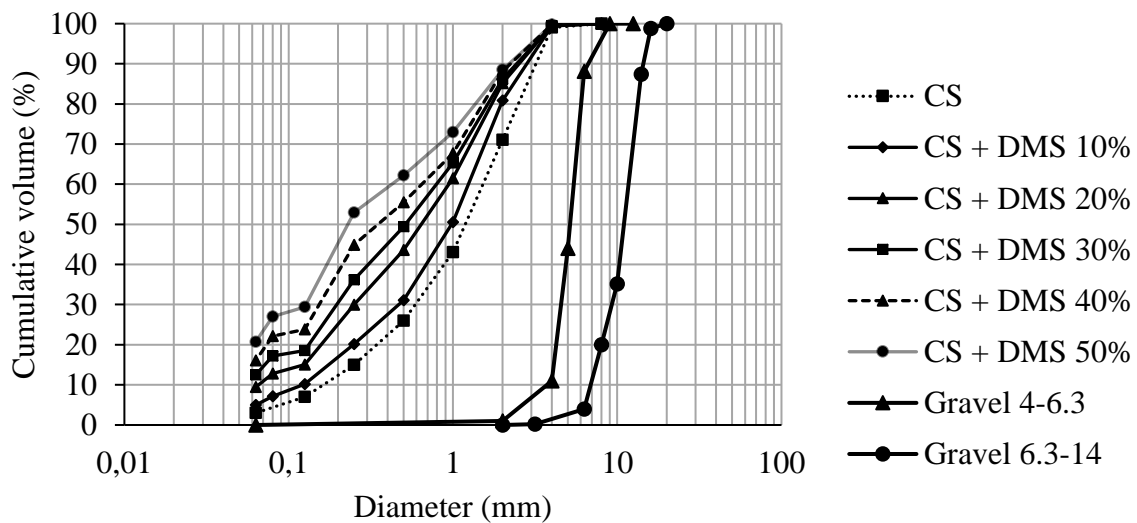
190 3- The CS-DMS mixtures were kept in hermetically sealed plastic bags at 20°C until use

191 The grain size distribution of CS and CS-DMS mixtures used in this study are illustrated in
 192 Figure 3 and their fineness modulus (FM) (according to ASTM C33), true density and water
 193 absorption (WA) ratio (according to NF EN 1097-6) are given in Table 6.

194 *Table 6. Fineness modulus, true density, and water absorption ratio of CS and CS-DMS mixtures used in this study. CS:*
 195 *Crushed sand. DMS: Dredged marine sediment. FM: Fineness modulus*

| | FM | True density (Mg/m ³) | Water absorption (%) |
|--------------|------|-----------------------------------|----------------------|
| CS | 3.23 | 2.62 | 1.40 |
| CS + DMS 10% | 2.78 | 2.55 | 2.40 |
| CS + DMS 20% | 2.37 | 2.47 | 3.20 |
| CS + DMS 30% | 2.18 | 2.39 | 4.10 |
| CS + DMS 40% | 1.95 | 2.32 | 5.30 |
| CS + DMS 50% | 1.70 | 2.25 | 6.90 |

196



197

198 *Figure 3. Particle size distributions of sand and gravels used in this study. CS: crushed sand. DMS: Dredged marine sediment.*

199 **2.4. Concrete mix design and specimen's preparation**

200 In this study, the Dreux-Gorisse method was applied to find the concrete formulation [27].

201 Table 7 presents an overview of the investigated specimens, their composition, and their

202 formulation properties.

203 Sample preparation was performed as follows. The solid contents, i.e., gravel, sand, binder and
204 DMS are first introduced and mixed for 60 seconds (s). Then, water is progressively added.
205 After 90 s, the superplasticizer is poured, and the constituents are mixed for 90 s.

206 After mixing, cylindrical specimens were cast in cylindrical cardboard molds of 110 mm
207 diameter and 220 mm height and covered with a plastic lid. After 24 hours of hardening, the
208 concrete specimens were removed from the molds and placed in water at 20°C for 28 days.

Table 7. Formulation properties and mixes design (Kg/m³) of concrete specimens used in this study.

| Concrete ID | 0% | 10% | 20% | 30% | 40% | 50% | 30% + 10L | 30% + 20L | 30% + SP2 | 0% + g | 30% + g | 0% wb=0.5 | 30% wb=0.5 | 0% wb=0.45 | 30% wb=0.45 |
|---------------------|--------|-------|-------|-------|-------|-------|-----------------|-----------------|-----------------|-----------|------------|--------------|---------------|---------------|----------------|
| Gravel 6.3/14 | 785.5 | 835.5 | 882.0 | 901.5 | 927.5 | 951.0 | 901.5 | 901.5 | 901.5 | 570.6 | 570.6 | 584.1 | 584.1 | 597.6 | 597.6 |
| Gravel 4/6.3 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 292.7 | 312.6 | 299.6 | 319.9 | 306.5 | 327.3 |
| CS | 1059.5 | 894.2 | 736.8 | 614.6 | 503.4 | 400.0 | 614.6 | 614.6 | 614.6 | 1004.0 | 645.3 | 1027.8 | 660.5 | 1051.5 | 675.8 |
| DMS | 0.0 | 99.35 | 184.2 | 263.4 | 335.6 | 400.0 | 263.4 | 263.4 | 263.4 | 0.0 | 276.6 | 0.0 | 283.1 | 0.0 | 289.6 |
| CEM1 52,5 | 238.0 | 238.0 | 238.0 | 238.0 | 238.0 | 238.0 | 238.0 | 238.0 | 238.0 | 238.0 | 238.0 | 238.0 | 238.0 | 238.0 | 238.0 |
| GGBS | 102.0 | 102.0 | 102.0 | 102.0 | 102.0 | 102.0 | 102.0 | 102.0 | 102.0 | 102.0 | 102.0 | 102.0 | 102.0 | 102.0 | 102.0 |
| Effective w | 181.5 | 181.5 | 181.5 | 181.5 | 181.5 | 181.5 | 181.5 | 181.5 | 181.5 | 181.5 | 181.5 | 165.0 | 165.0 | 148.5 | 148.5 |
| w/b ratio | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.55 | 0.50 | 0.50 | 0.45 | 0.45 |
| WC G (%) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| WC g (%) | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 | 0.0 |
| WC CS (%) | 0.0 | - | - | - | - | - | - | - | - | 0.0 | - | 0.0 | - | 0.0 | - |
| WC CS+DMS (%) | - | 0.3 | 1.3 | 1.8 | 2.9 | 3.8 | 1.0 | 1.0 | 1.0 | - | 2.4 | - | 2.4 | - | 3.2 |
| Mixing w | 202.0 | 208.5 | 205.5 | 208.0 | 207.5 | 212.5 | 224.5 | 234.5 | 214.5 | 202.2 | 204.1 | 186.2 | 188.0 | 170.2 | 164.3 |
| SP1 (%) | 0.1 | 0.2 | 0.5 | 1.2 | 1.6 | 2.0 | 1.2 | 1.0 | - | 0.1 | 1.0 | 0.2 | 1.7 | 0.5 | 2.8 |
| SP2 (%) | - | - | - | - | - | - | - | - | 1.1 | - | - | - | - | - | - |
| Paste volume (L) | 307.3 | 321.6 | 337.2 | 347.6 | 359.1 | 373.6 | 347.6 | 347.6 | 347.6 | 306.1 | 347.9 | 289.8 | 332.5 | 273.4 | 317.1 |
| Gravel/Sand | 0.72 | 0.81 | 0.89 | 0.93 | 0.99 | 1.04 | 0.93 | 0.93 | 0.93 | 0.85 | 0.88 | 0.85 | 0.88 | 0.85 | 0.88 |

210 CS: crushed sand, DMS: Dredged marine sediment, GGBS: Ground Granulated Blast-furnace Slag, w: water, wb ratio: water to binder ratio

211 WC: water content, G: gravel 6.3/14, g: gravel 4/6.3, SP: superplasticizer, Mixing water = Effective water + WA of aggregates

212 **2.5. Methods**

213 2.5.1. Slump test

214 In order to analyze the effect of CS substitution by DMS on the properties of fresh concrete,
215 the slump test was used after mixing concrete according to NF EN 12350-2 [32]. The targeted
216 slump test after the addition of SP was $190 \text{ mm} \pm 25 \text{ mm}$ which gives a plastic concrete of class
217 S4. Then, the effect of DMS on the concrete workability was evaluated by the amount of SP
218 added to achieve this targeted slump.

219 2.5.2. Mechanical compressive strength

220 The compressive strength tests (MPa) were carried out following NF EN 12390-3 standards
221 [33]. A total of 3 specimens of each concrete type were tested at 28 days using compression
222 testing machine (3R, France). The axial loading rate on each sample was 0.5 MPa/second.

223 2.5.3. Water porosity and water absorption

224 Water porosity and water absorption experiments were carried out at 28 days, following NF
225 P18-459 [34] and NF EN 13369 [35] standards, respectively. Three samples (110 mm diameter
226 and 50 mm height) of each concrete preparation were soaked in water for 48 h under pressure
227 (vacuum saturation) and at atmospheric pressure (Water Absorption by Immersion, WAI) in
228 the case of water porosity and water absorption respectively. The wet mass was measured after
229 drying off each sample surface. For the dry mass, the samples were dried in an oven at 105°C
230 to attain a constant weight with a tolerance of $<0.05\%$ of each sample weight.

231 2.5.3. Statistical analysis

232 To evaluate the significant effect of DMS on the concrete properties, statistical analysis was
233 performed using one-way ANOVA tests on GraphPad Prism 5 (GraphPad Software, San Diego,
234 CA, USA).

235 **3. Results and discussion**

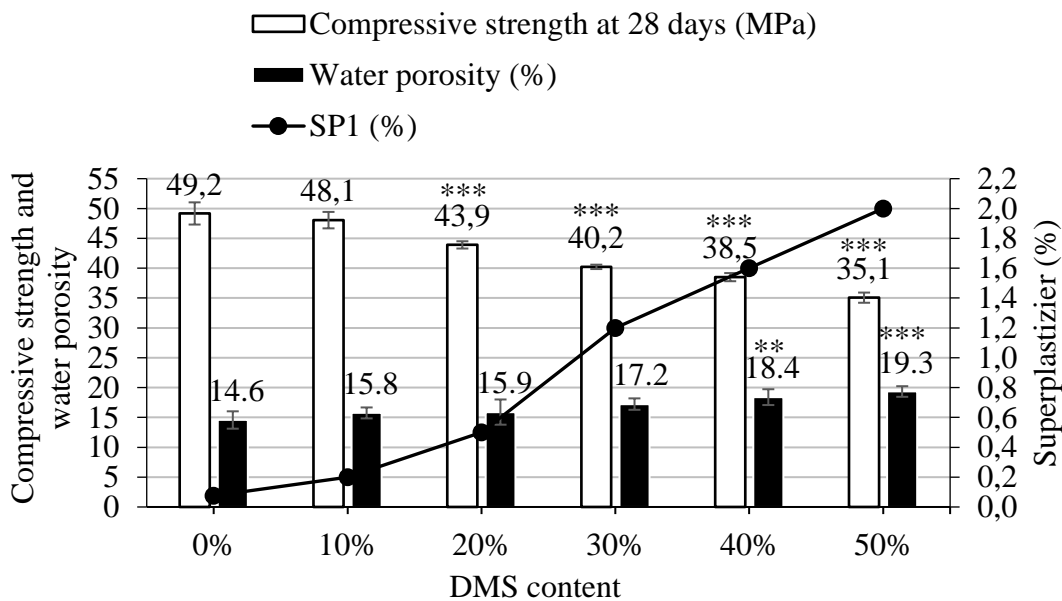
236 **3.1. Effect of DMS on concrete workability**

237 Workability is one of the most important characteristics of fresh concrete. It is the main property
238 that indicates the ability of concrete to be reshaped, moved and consolidated [36]. Figure 4
239 shows that the workability of concrete decreases with increasing DMS content. Consequently,
240 the quantity of SP (% by binder weight) added to attain the targeted slump ($190 \text{ mm} \pm 25 \text{ mm}$)

241 increases when CS substitution by DMS increases. The SP requirement was 0.1% and 2.0%
 242 when the CS substitution by DMS was 0% and 50% respectively. These results are consistent
 243 with the study of Limeira et al [37]. In their study, Limeira *et al.* used additional plasticizer
 244 content when the sand was replaced by DMS in concrete mixes.

245 According to studies on concrete rheology, concrete workability is affected by many factors:
 246 (i) the amount and the type of binder, (ii) the Physico-chemical properties and the amount of
 247 fine and coarse aggregates, (iii) the amount and the type of chemical admixtures, (IV) water
 248 and the time and method of mixing ... [38,39]. In this present study, the reduced workability of
 249 the concrete made with DMS can be justified by:

- 250 1. The angular shape and the rough surface of the DMS (Figure 5) [40]; According to
 251 [36], the angular fine aggregate particles interlock and reduce the freedom of
 252 movement of particles in the fresh concrete.
- 253 2. The number of fine particles (38.5%), the high specific surface area (3.14 cm²/g, Table
 254 1) and water absorption ratio of DMS and CS-DMS mixtures (Table 6) [41];
 255 According to [42], the mixing water in concrete preparation exists in the forms of free
 256 layer water, adsorbed layer water and filling water. Among these forms of water, only
 257 the free layer of water contributes to concrete workability by separating solid particles.
 258 However, the amount of adsorbed layer water increases with the increase in surface
 259 area and the percentage of fine particles [3].

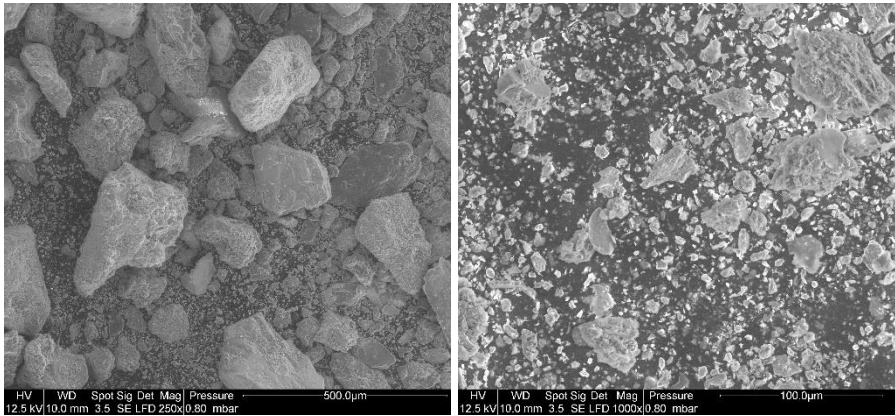


260

261 *Figure 4. Effect of DMS on concrete workability, compressive strength, and water porosity). 0, 10, 20, 30, 40, and 50% present*
 262 *the substitution rate of crushed sand by dredged marine sediment. All experiments were performed in triplicate and the error*

263 bars present the standard deviation of the obtained values. The experiments highlighted with asterisks differed significantly
264 from the control (Bonferroni; **: $p < 0.01$, ***: $p < 0.001$)

265



266

267 *Figure 5. Scanning electron microscopy images of dredged marine sediment used in this study.*

268 **3.2. Effect of DMS on water porosity**

269 In the marine environment, the water porosity of concrete is one of its most important
270 characteristics, which strongly affects its mechanical behavior and service life [43]. Generally,
271 an increase in concrete porosity leads to a reduction in compressive strength [44]. However,
272 concrete porosity plays an important role with regard to the primary durability issues in
273 seawater (external aggression, including chloride penetration) [45]. The effect of DMS on the
274 water porosity of concrete specimens is shown in Figure 4. The results show that the water
275 porosity increases with the increase of DMS content. The water porosity increases non-
276 significantly from 14.6% to 17.2% when the substitution rate was 0% and 30% respectively.
277 Then, the increase in water porosity becomes significant and reaches a value of 19.3% at a
278 substitution rate of 50%. These results are in keeping with the study of [46] which showed that
279 the porosity increases when the rate of sediment substitution increases. In this study, the
280 increase in water porosity could be justified by the increase in the paste volume of concrete
281 made with DMS (Table 7) and by the increase in the water absorption ratio of CS-DMS
282 mixtures with an increasing substitution rate (Table 6).

283 **3.3. Effect of DMS on mechanical resistance**

284 The effect of DMS on the compressive strength of concrete is shown in Figure 4. The results
285 indicate that the strength of concrete decreases with the increase in the proportion of DMS. At
286 10% of DMS content, the decrease in compressive strength (48.1 MPa) is not significant
287 compared to the control (0%, 49.2 MPa). Contrariwise, using a substitution rate higher than

288 10% significantly affects the mechanical resistance of concrete specimens ($P_{\text{value}} < 0.001$).
289 These results are in line with the study of Moradi and Shahnoori [22], in which the compressive
290 strength of concrete specimens was negatively affected by the use of DMS content higher than
291 15%. However, based on the results of compressive strength analysis in this study,
292 incorporating DMS as CS substitute in marine concrete at a rate lower than 50% is feasible,
293 while retaining 38 MPa as the minimum compressive strength at 28 days.

294 The compressive strength of concrete is influenced by many factors including porosity, grain
295 size distribution of aggregates, maximum size of aggregates, water to binder ratio, surface
296 texture and strength [47]. As noted by Beddaa et al., 2020, the fine particles of sediments affect
297 the properties of cement paste: because of to their specific surface area and water demand, fines
298 and clay reduce workability and could also affect strength and durability. In this present study,
299 the decrease in mechanical resistance may be attributed to (i) the effect of DMS on the pore's
300 distribution and on the water porosity of concrete specimens (ii) the distribution (by DMS) of
301 the organized granular arrangement formed by the conventional aggregates [48] (iii) the
302 increase of the percentage of fine particles ($<63 \mu\text{m}$) in CS-DMS mixtures (Figure 3) and (IV)
303 the chemical composition of DMS (i.e. salt content) (Table 1) [49,50].

304 **3.4. Selection of substitution percentage**

305 According to the slump, water porosity and compressive strength tests, a XS2 concrete C30/37
306 could be designed with 10% of sand replaced by DMS without significantly affecting the
307 concrete properties. Therefore, DMS can be used as sand replacement in marine concrete
308 manufacturing. However, a substitution rate of 30% is the highest DMS percentage that (i)
309 required no more than 2% of SP to achieve the targeted slump, (ii) allowed a compressive
310 strength higher than 38 MPa (38.5 MPa) and (iii) did not significantly affect the water porosity
311 of concrete. Accordingly, the substitution rate of 30% was selected to optimize the concrete
312 mix design using DMS as sand replacement. The objective was to minimize as much as possible
313 the differences in the properties of the reference concrete and the concrete made with DMS.

314 **3.5. Optimization of concrete mix design**

315 The quantity of mixing water ($+ 10 \text{ L/m}^3$, $+ 20 \text{ L/m}^3$), the superplasticizer (SP2), the granular
316 arrangement and the water to binder ratio ($w/b = 0.50$, $w/b = 0.45$) are the parameters used to
317 optimize the concrete mix design made with 30% of sand substitution by DMS.

318 The results of superplasticizer quantity, compressive strength at 28 days, water porosity and
319 water absorption of the optimized concrete specimens are shown in Figure 6.

320 3.5.1. The quantity of mixing water

321 The quantity of mixing water is the first parameter to be optimized when the objective is to
322 improve the durability of concrete. In this study we have used an excess quantity of water (+
323 10 L/m³, + 20 L/m³) during the preparation of concrete made with CS-DMS to verify the
324 calculation accuracy of water quantity added to concrete mixes according to the water
325 absorption ration of CS-DMS (4.1%, Table 6). If the water absorption ratio of the CS-DMS is
326 greater than the calculated ratio, the use of excess water does not influence the properties of
327 hardened concrete. As shown in Figure 6, the compressive strength and the porosity of concrete
328 specimens decrease and increase respectively with the increase of excess water. These results
329 are in agreement with the technical sheet of Holcim Group [51] ; “each additional 10 liters of
330 water per cubic meter will reduce the strength of concrete by about 2.5 MPa”. These results
331 confirm the accuracy of water mixing quantity used in the preparation of concrete specimens.

332 3.5.2. The superplasticizer

333 The fresh and hardened characteristics of concrete can be modified and controlled with
334 superplasticizers [52]. However, the compatibility between the superplasticizer chosen and the
335 cement used is a very important factor in concrete manufacturing. In the case of incorporation
336 of mineral additions to Portland cement, several studies have been carried out to test the
337 compatibility between superplasticizer and blended cement. The findings of these studies show
338 that the effectiveness of superplasticizer is influenced by several factors such as the
339 superplasticizer family, the mechanisms involved in superplasticizer action (electrostatic
340 mechanism, steric obstacle...), the presence and the quantity of Ca(OH)₂ and the physio-
341 chemical properties of Portland cement and minerals additives [53–56]. To the best of our
342 knowledge, no information regarding the effectiveness of superplasticizer has been published
343 when a DMS was used in concrete preparation. Therefore, in this study, a superplasticizer
344 named SP2 was tested during the optimization of concrete mix design. Although SP2 belongs
345 to the same family of SP1 (Polycarboxylate), the results show that SP2 (i) more effectively
346 improves the concrete workability (Figure 6 A), (ii) improves the mechanical strength and the
347 water porosity (compared to SP1) (Figure 6 B and C), (iii) gives the same water absorption
348 compared to the control (5.9%) (Figure 6 D). Knowing the reasons of these differences will be
349 the subject of a future study in our laboratory.

350 3.5.3. The granular arrangement

351 According to the literature, the aggregate used in concrete preparation affects the properties of
352 fresh and hardened concrete [57]. Therefore, a gravel with size ranged from 4 to 6.3 mm was
353 used in the optimization process to ensure the correct grain size distribution between the sand
354 (0/4 mm) and the coarse gravel (6.3/14 mm). The results show that the use of gravel 4/6.3 mm
355 improves the workability of concrete specimens in such a way that a smaller amount of SP was
356 required to attain the targeted slump (190 mm \pm 25 mm); the amount of SP added to attain the
357 targeted slump is 1.2% and 1% (by cement weight) for the concrete without and with gravel
358 4/6.3 mm respectively. However, when the gravel 4/6.3 was used, (i) the compressive strength
359 decreased slightly (2 and 0.2 MPa in the case of control concrete and concrete made with 30%
360 DMS respectively), (ii) the water porosity increased slightly (0.8 and 0.7% in the case of control
361 concrete and concrete made with 30% DMS respectively) and (iii) the water absorption
362 increased slightly (0.5 and 0.8% in the case of control concrete and concrete made with 30%
363 DMS respectively). Accordingly, the use of an intermediate gravel improves the fresh
364 properties (the workability) and does not affect the hardened properties of concrete specimens.
365 The slight differences observed at the hardened state can be attributed to the characteristic
366 differences between the gravel 4/6.3 and 6.3/14 (Table 4). Therefore, the intermediate gravel
367 4/6.3 was used in the concrete mix designs with w/b ratio of 0.50 and 0.45.

368 3.5.4. The water to binder ratio

369 In order to improve the durability of concrete, concrete specimens with a water to binder ratio
370 of 0.50 and 0.45 were prepared. According to AFGC (French Association of Civil Engineering)
371 the durability and the lifetime of marine concrete can be estimated according to the water
372 porosity value and other durability indicators such as the permeability and the chloride diffusion
373 coefficient [58]. Table 8 shows the potential durability and the estimated lifetime of marine
374 concrete based on the porosity value. Therefore, according to AFGC, the concrete specimens
375 prepared with a water to binder ratio of 0.55 (w/b =0.55, SP2, and +g 4/6.3) have a very low
376 and a low potential durability in the case of control concrete (0%) and concrete made with 30%
377 DMS respectively (Figure 6 C).

378 *Table 8. Potential durability and estimated lifetime of concrete structure according to the water porosity value (AFGC, 2004).*

| Water Porosity value (%) | 16-15 | 15-14 | 14-12 | 12-9 | <9 |
|----------------------------|----------|-------|--------|---------|-----------|
| Potential durability | Very low | low | Medium | High | Very high |
| Estimated lifetime (years) | < 30 | 30-50 | 50-100 | 100-120 | >120 |

379

380 However, according to NF EN 206 [26], the water absorption value of marine concrete (XS2)
381 must not be exceed 6%. Consequently, the water absorption ration of concrete specimens
382 prepared with a water to binder ratio of 0.55 (w/b =0.55, SP2, and +g 4/6.3) does not meet the
383 standard requirements (NF EN 206) (Figure 6 D).

384 Therefore, reducing the w/b ratio is necessary to improve the potential durability and the
385 estimated lifetime of concrete made with DMS. As expected, the results presented in Figure 6
386 show that the decrease of the w/b ratio has the following consequences:

- 387 • The quantity of SP (% by binder weight) required to attain the targeted slump (190 mm
388 ± 25 mm) increases. In the case of w/b ratio of 0.45, the quantity of SP added is greater
389 than 2% for the concrete made with DMS.
- 390 • The compressive strength increases
- 391 • The water porosity and water absorption decrease. The water absorption ratio is less
392 than 6%.

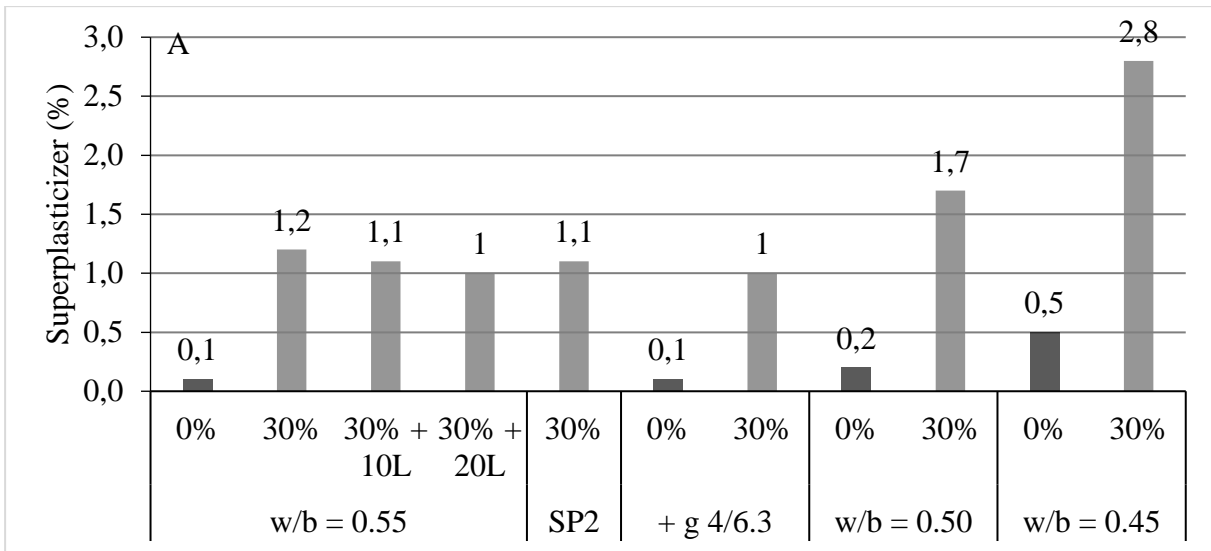
393 However, according to the water porosity, the concrete specimens made with DMS (30% as
394 sand substitution) have the same potential durability (medium and high for w/b ratio of 0.50
395 and 0.45 respectively) and the same estimated lifetime (between 50-100 years and between 100-
396 120 years for w/b ratio of 0.50 and 0.45 respectively) as the concrete specimens made with CS.
397 Thus, XS2 concrete C30/37 could be designed with 30% of sand replaced by DMS (which have
398 the same physio-chemical properties of the DMS presented in this study) without significantly
399 affecting the potential durability and the estimated lifetime of the concrete structure.
400 Accordingly, in order to use the maximum rate of sand substitution by DMS in marine concrete
401 without using an excessive amount of SP, the concrete specimens should be prepared with an
402 intermediate gravel and a water to binder ratio of 0.5.

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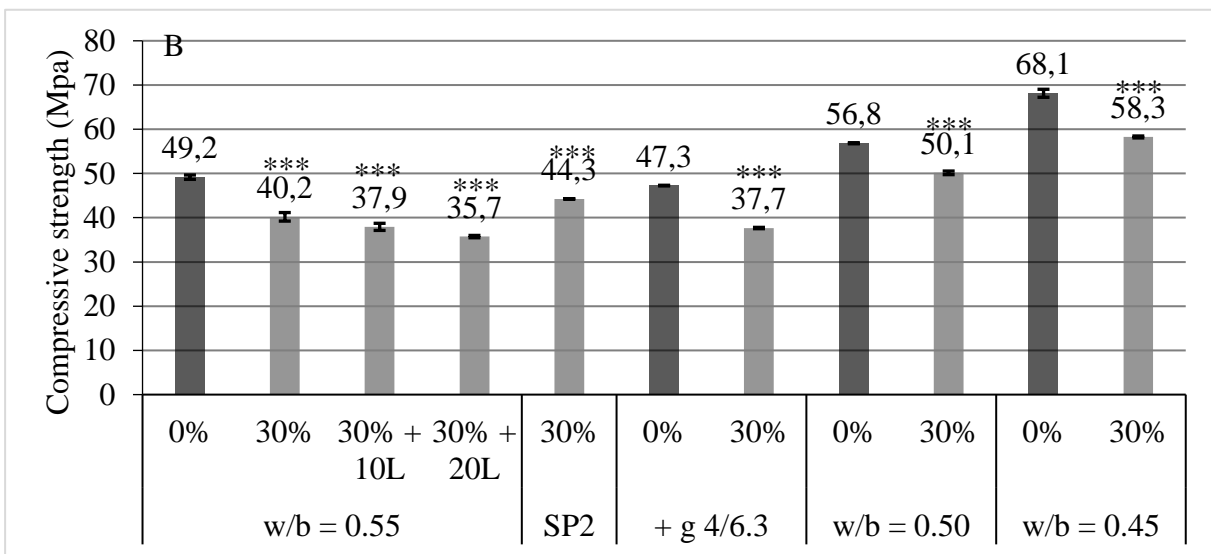
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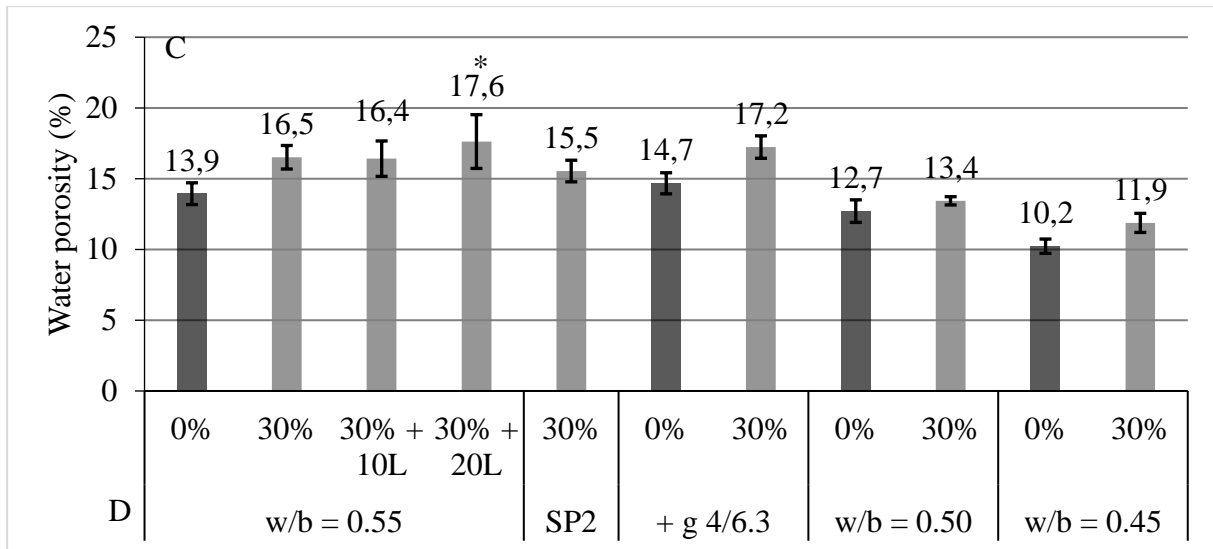
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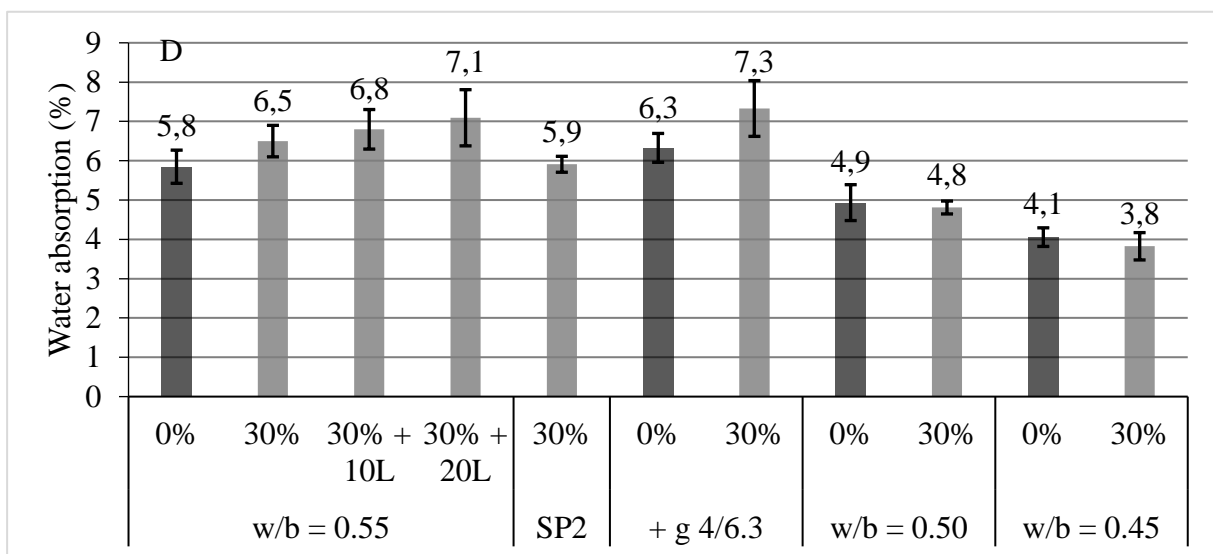
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410 *Figure 6. Superplasticizer, Compressive strength at 28 days, water porosity and water absorption of concrete specimens*
 411 *prepared during the optimization of concrete mix design. All experiments were performed in triplicate and the error bars*
 412 *represent the standard deviation of the obtained values. The experiments highlighted with asterisks differed significantly from*
 413 *the control (Bonferroni; *: $p < 0.1$, ***: $p < 0.001$)*

414

415 **4. Conclusions**

416 With the large volume of marine sediments dredged annually and the ever-increasing demand
 417 for construction materials, the development of a new type of construction materials by using
 418 the dredged sediments would offer a global opportunity in terms of economy and environment.
 419 In this study, the effects of untreated marine sediments used as crushed sand replacement on
 420 the workability, compressive strength, water porosity and water absorption of concrete
 421 specimens were investigated. The following conclusions can be inferred from the results of this
 422 experimental study:

- 423 1. The partial substitution of crushed sand with dredged marine sediment (dominated by
424 fine-grained sediment) affects the fresh properties of the concrete. The workability of
425 concrete decreases with the increase of the substitution rate.
- 426 2. The compressive strength of concrete decreases significantly when the substitution rate
427 exceeds 10%.
- 428 3. The water porosity of concrete decreases significantly when the substitution rate
429 exceeds 30%.
- 430 4. The quantity of mixing water, the chosen superplasticizer, the granular arrangement,
431 and the water to binder ratio are conditions that should be optimized in order to produce
432 a suitable concrete made with dredged marine sediment.
- 433 5. Based on the results of concrete mix design optimization, a marine concrete XS2,
434 C30/37 could be designed with 30% of sand replacement by dredged marine sediment
435 (which have the same physio-chemical properties of the DMS presented in this study)
436 without significant impact on the potential durability and the estimated lifetime of
437 concrete structure.

438 This paper presents a part of results of the ECODREGE MED II project. Based on the results
439 obtained in this part of project, the designed and optimized concrete mix will be used for the
440 following investigations:

- 441 1. Economic and environmental impact assessment of this new concrete made with DMS
442 using life cycle assessment and life cycle cost assessment [59].
- 443 2. Investigating the rheological properties of concrete made with dredged marine sediment
444 using mortar specimens.
- 445 3. Identifying the effects of replacing sand with 30% of marine sediment on the concrete
446 durability parameters such as chloride diffusion, gas permeability...
- 447 4. Pilot implementation of a marine concrete structure through partial replacement of sand
448 by dredged marine sediments, in collaboration with the concrete industry.

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