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# Use of uncontaminated marine sediments in mortar and concrete by partial substitution of cement

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ABSTRACT

The disposal of dredged marine sediments has become a major economic and environmental issue in the world. In this study, uncontaminated marine sediments dredged in the harbor of Dunkirk (France) were dried and ground and then used in partial substitution of cement in the manufacture of mortars and concretes. A given volume of cement has been replaced by the same volume of sediment for three substitution contents (10%, 20%, 30%) of a Portland cement CEM I 52.5. The flexural and compressive strengths of mortars decreased when the sediment replacement content increased. However, the mechanical properties of the mortar with 20% replacement of cement with sediments were better than those of a mortar made from cement CEM II/A-LL 32.5 containing a proportion of limestone similar to the sediment substitution. The total porosity measured by mercury intrusion porosimetry of different types of mortars showed that the porosity increased as the sediment substitution content increased but the pore size distribution was shifted toward smaller pores. Finally, it was demonstrated that concrete C30/37 could be designed with 20% cement replaced by sediment without the use of admixture. Additionally, this concrete fulfilled the standards with respect to the total chloride content required for unreinforced concrete. As a conclusion, dried and finely ground uncontaminated sediments appeared to be a very interesting constituent for partially substituting up to 20% of cement as its efficiency overpass limestone filler.

## 1. Introduction

A large amount of sediment is dredged for navigation every year. In France, about 50 million $m^3$ of sediment are produced from harbors. While in China, about 400 million $m^3$ of sediment are dredged annually [1]. Thus, the disposal of dredged sediment has become a major economic and environmental issue in the world [2–4]. The sediment can contain a variable amount of organic pollutants (PAHs: polycyclic aromatic hydrocarbons, PCBs: polychlorinated biphenyls, TBT: tributyltin and dioxins) and different levels of inorganic contaminants (heavy metals such as As, Cd, Pb, Cr, Cu, Ni, Hg and Zn).

Polluted sediments can be treated for example by Novosol process which consists of two major phases: phosphatation (2–3.5% of phosphoric acid $H_3PO_4$) and calcinations at ≥ 650 °C [5]. Treated sediments have been successfully incorporated into the brick production as a raw material [6,7]. The industrial-scale experiment showed that bricks made of sediments would have no environmental impact restricting their application [8]. So far, a lot of research are devoted to reuse marine dredged sediments as a new material resource as foundation and base layers for road construction [9–14]. The results showed that the solidification/stabilization of sediment by using cement, lime and other additives such as fly ash and slag can satisfy the mechanical properties specification and the prescribed thresholds for environmental impact [10,13].

However, there are fewer studies on the reuse of sediments in mortar or concrete comparing to the reuse of sediment in the road construction [15–18]. Concrete is the first material used in the world which needs very large amounts of cement, aggregate and water [19,20]. In the last decades, the interest of reusing recycled aggregate and sand or recycled filler in the concrete industry was demonstrated [21–26]. Following this trend, it thus appears that the use the sediment in the manufacture of mortars and concretes is very promising [27,28]. Some authors reported the production of lightweight coarse aggregate (LWA) at the temperatures of 1100–1200 °C by using sediments for the

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masonry and concrete [29,30]. The results showed that the LWA ranged from 1010 to 1380 kg/m$^3$ for the particle density, and met the requirement for the lightweight aggregate. The concrete made from sedimentary LWA ranged from 19.8 to 34.7 MPa, can satisfy the requirement for structural lightweight concrete [30]. Some authors investigated the possibility of sediments as sand in the cement-based materials [2,18,31]. Agostini et al. replaced sand by sediment treated by Novosol process at substitution levels of 33%, 66% and 100% [31]. Despite that the fine fraction of sediment had a high porosity leading to a higher amount of absorbed water and greater drying shrinkage of mortar, mortars made with 33% of sediment showed significant compression strength improvement (up to 20%). The formation of a denser interfacial transition zone in the presence of treated sediment was expected to be at the origin the reported mechanical strength improvement [2,31]. Couvidat et al. also indicated that the use of the coarse fraction marine sediment offered an interesting valorization potential as sand in the cement mortars for non-structural applications [18].

Some authors studied the use of contaminated sediment to replace a portion of raw materials in the production of Portland cement clinker [32,33]. Aouad et al. showed that the laboratory manufactured cement based on the sediment produced the equivalent compressive strengths to those commercially produced Portland cement [32]. Dang et al. investigated the new blended cements made of a mixture of Portand cement and 8%, 16% and 33% of thermally treated sediment at 650 °C and 850 °C. The blend cement based on the sediment treated at 650 °C involved higher compressive strength than the one based on the classical calcareous filler [34]. Rozière et al. studied the use of treated sediments at 650 °C in self-consolidating concrete as a replacement of limestone filler and aggregates. The compressive strength of sediment-based concrete specimen was comparable to that of reference concrete [35].

However, fewer studies were devoted to the valorization of uncontaminated marine sediment just subjected to drying at ambient temperature for long period or at moderated temperature if the process has to be speed up. This study is thus reporting the use of marine sediments, dried at 40 °C and then ground, as partial substitution of cement in the manufacture of mortars and concretes. Three contents of sediments were used as cement CEM I 52.5 substitution (10%, 20%, 30%) to produce mortars. The fresh properties such as fresh density, slump and the mechanical properties of mortars were measured and the microstructural properties of mortars were also studied. Finally concretes were designed from the results obtained on mortars.

## 2. Materials and methods

### 2.1. Sediments characterization

The used marine sediments were dredged in the port of Dunkirk (France). The measured initial water content of sediment was about 95%. The clay fraction activity was low (3.2% measured by the methylene blue test). Then they were dried at 40 °C until constant weight and then ground in a laboratory mill (The treatment of 40 °C consumes less energy comparing to the treatment at 650 °C. Here, grinding is necessary in order to use to use all fractions of sediment). In this study, the fraction 0/80 μm was used for partially replacing cement in the manufacture of mortars. The organic matter content was measured as 13.8% according to the standard XP P94-047 [36] by calcination in oven at 450 °C for 3 h. The true density was 2.48 g/cm$^3$ measured by helium pycnometer, which is lower than Portland cement.

Table 1 shows the chemical composition of sediment determined by X-ray fluorescence. The major chemical elements of the sediment were oxygen, silicon, calcium, aluminum and iron. PAHs (polycyclic aromatic hydrocarbons) value was 0.29 mg/kg and PCBs (polychlorinated biphenyls) value was 6.34 mg/kg, which were under the limited value according to AMATR [37]. Table 2 shows the average values of leaching test results with a liquid to solid ratio of ten according to standard EN 12457–2 [38]. Metallic elements and ions such as chlorides and sulphates were analyzed. According to the prescribed limits criteria and procedure for the acceptance of waste at landfills in European directive 2003/33/CE [39], all the heavy elements were in the limit of Class III (inert waste) except for the Mo and Se in the Class II (non-hazardous waste). Thus the sediments were not contaminated with heavy metals but they contained a high chloride content that impacts the mix design of concrete. Indeed, chloride ions can catalyze the corrosion of steel rebar contained in reinforced concrete. For these reasons, limits of the amount of chloride in cement and thus in the present case, of the amount of marine sediment, will depend on the type of concrete and its usage as defined in the standard EN 206–1 [40] (Table 3). The aim was to use the maximum quantity of sediment in the concrete mix design, thus unreinforced concrete was targeted in order to keep the chloride content at value less than 1% relative to the cement.

**Table 1**
Chemical composition of sediment.

| Element symbol | Element name | Percentage (%) |
|---|---|---|
| O | Oxygen | 50.2 |
| Na | Sodium | 1.8 |
| Mg | Magnesium | 1.1 |
| Al | Aluminum | 4.6 |
| Si | Silicon | 16.5 |
| P | Phosphorus | 0.1 |
| S | Sulfur | 1.5 |
| Cl | Chlorine | 2.1 |
| K | Potassium | 1.5 |
| Ca | Calcium | 16.2 |
| Ti | Titanium | 0.3 |
| Fe | Iron | 3.7 |
| Pb | Lead | 0.1 |
| C | Carbon | Present |
| Mn | Manganese | Traces < 0.1 |
| Cr | Chromium | Traces < 0.1 |
| Cu | Copper | Traces < 0.1 |
| Zn | Zinc | Traces < 0.1 |
| Sr | Strontium | Traces < 0.1 |
| Zr | Zirconium | Traces < 0.1 |
| V | Vanadium | Traces < 0.1 |

**Table 2**
Leaching test results and limiting values of classification of wastes from 2003/33/CE.

| Tests | ICP (Inductively Coupled Plasma) values | 2003/33/CE Class III: inert waste | 2003/33/CE Class II: non-hazardous waste | 2003/33/CE Class I: hazardous waste |
|---|---|---|---|---|
| pH | 8.74 | – | – | – |
| As (mg/kg) | 0.117 | < 0.5 | < 2 | < 25 |
| Ba (mg/kg) | 0.909 | < 20 | < 100 | < 300 |
| Cd (mg/kg) | 0.009 | < 0.04 | < 1 | < 5 |
| Cr (mg/kg) | 0.043 | < 0.5 | < 10 | < 70 |
| Cu (mg/kg) | 0.485 | < 2 | < 50 | < 100 |
| Mo (mg/kg) | 1.101 | < 0.5 | < 10 | < 30 |
| Ni (mg/kg) | 0.076 | < 0.4 | < 10 | < 40 |
| Pb (mg/kg) | < 0.082 | < 0.5 | < 10 | < 50 |
| Sb (mg/kg) | 0.118 | < 0.06 | < 0.7 | < 5 |
| Se (mg/kg) | 0.135 | < 0.1 | < 0.5 | < 7 |
| Zn (mg/kg) | 0.125 | < 4 | < 50 | < 200 |
| Chlorides (mg/kg) | 20555 | < 800 | < 15000 | < 25000 |
| Sulfates (mg/kg) | 3485 | < 1000 | < 20000 | < 50000 |

### 2.2. Mix design of mortars

Portland cement CEM I 52.5 and CEM II/A-LL 32.5 were used to produce reference mortars. The density of these two cements measured