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Technical Note

# Strength and deformation properties of Dunkirk marine sediments solidified with cement, lime and fly ash

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ABSTRACT

Most of the previous studies concerning solidification of dredged sediments focus mainly on the strength and environmental properties, but the deformation properties have not been fully appreciated. The present study emphasizes the deformation characteristics of marine sediments by using deformation parameters. A series of unconfined compression tests was performed on about 150 standard samples of 13 designed mixes. After analyzing the stress–strain curves of different mixes at 14, 28, 60 and 90 days, the effect of binder content (as cement, lime and fly ash) on peak strength and failure strain is discussed. It can be found that addition of fly ash improves the mechanical performance of lime-treated sediments, but damages the strength of cement-treated sediments. The lime-fly ash binder can substitute lime and cement-fly ash binder to solidify sediments owing to lower cost, waste recycling and good ability to gain strength. The concept of strength ratio is introduced to evaluate the development of unconfined compressive strength with curing time and binder content. By comparison, the relationship between failure strain and unconfined compressive strength is calculated as $\sigma = (20\text{–}130)\,\varepsilon_f$ and the failure strain ranges mainly between 1% and 2%. The deformation modulus defined at 50% of peak strength is explored for designed materials at different binder contents and different curing times. The development of deformation modulus is in accordance with unconfined compressive strength. A quantitative correlation $E_{50} = 119.91$ *UCS* is therefore determined according to large quantities of test results. Finally, the microstructure of solidified sediments is observed by using scanning electron microscopy.



## 1. Introduction

Sediments are defined as a set of loose particles of clay, silt and sand, formed from the erosion of rocks and soils, from organic activity, and from local discharges caused by human activities (Life, 2002; Dubois et al., 2011). To maintain sufficient depth in harbors for the circulation of ships, sediments are dredged annually from coast and estuarine lines throughout the world. Over 600 $Mm^3$ (Boutin, 1999) and 33.56 Mt (dry mass) (Le Guyader, 2012) of dredged sediments are produced each year in the world and in France. However, due to various human activities, sediments contain generally a variable amount of inorganic components (heavy metals, metalloids elements and some salts including sulfate, chlorides and nitrate) and organic components (polycyclic aromatic hydrocarbons, polychlorobiphenyl and organochlorine pesticides) (Alzieu, 1999; Le Hecho, 2001). In the context of sustainable development, traditional solutions, such as ocean immersion and land disposal, become less and less authorized due to pollution or land occupation of abandoned sediments, although dumping at sea is possible in compliance with the environmental recommendations in European countries. Hence several alternatives of sediment reuse such as solidification/stabilization technique are developed in many domains as civil engineering to avoid pollution and produce new soil materials.

Solidification/stabilization technique is an attractive technology for various wastes including sediments by using cement, lime and other binders to reduce their toxicity and improve their strength properties prior to ultimate disposal (Valls and Vàzquez, 2000; Dermatas and Meng, 2003; Qian et al., 2008; Silitonga et al., 2009; Levacher et al., 2011; J. Wang et al., 2012; Miqueleiz et al., 2012; Zentar et al., 2012). Due to the available large quantity and advantages of a renewable resource, many authors in France have used the solidification/stabilization technique to improve the physical, mechanical and environmental properties of dredged sediments from Dunkirk harbor (Aouad et al., 2012; D. Wang et al., 2012; Zentar et al., 2012), port of Le Havre (Boutouil, 1998), Rouen harbor (Colin, 2003), Port-En-Bessin harbor (Silitonga, 2010; Silitonga et al., 2010), Cannes harbor (Levacher and Sanchez, 2011; Levacher et al., 2011) and a channel linking Charleroi

*Abbreviations:* $\omega_i$, initial water content; $\rho_s$, absolute density; LL, liquid limit; PL, plastic limit; PI, plasticity index; UCS, unconfined compressive strength; $\sigma$, stress; $\varepsilon$, strain; $\varepsilon_f$, failure strain; $E_{50}$, deformation modulus at 50% of UCS.

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to Brussels (Scordia, 2008; Scordia et al., 2008). They have adopted either the skeleton constructing method by using binder (as cement, lime and fly ash) and/or granular materials (as sand and slag), or the thermal treatment method such as Novosol® process (Kribi, 2005; Zoubeir et al., 2007; Nguyen, 2008; Scordia, 2008). No matter which method is used, objectives are focused mainly on: (a) changing the initial fluid flow state of sediments, (b) eliminating or stabilizing the hazardous materials such as heavy metals and organic matters, (c) improving the mechanical performance and (d) producing new geomaterials or granular materials to solve the problem of high-quality resource shortage. Fortunately, the above-mentioned literatures showed that the solidified sediments are suitable and adequate materials for filling engineering, pavement construction, cement production, light-weight concrete production and brick fabrication.

The transformation of dredged sediments into geomaterials is an attractive technology to relieve the shortage of high-quality materials in various projects, such as coastal highway. This will facilitate the recycling of dredged materials from local sources and save natural soil resources and transportation costs for seaside construction. In France, the domain of civil engineering consumes over 450 Mt of granular materials each year (UNPG, 2007), and 50.7% of such materials are annually consumed in the field of road construction (Michel, 1997). However, only 5% of the materials generated from recycling operation are used in public works at present (UNPG, 2007). This data indicates that in the context of sustainable development it is still necessary to study and recycle sediments as renewable geomaterials.

According to the cited literature, most studies generally focus on the potential utilization of raw sediments and sediments-based materials in different fields, mainly from the physical, mechanical and environmental viewpoints. However, not many comprehensive studies could be found to evaluate the effect of different binders especially siliceous–aluminous fly ash on strength and deformation properties of Dunkirk solidified sediments, such as stress–strain curves, failure strain and deformation modulus. Consequently, this paper aims at (a) investigating the stress–stain curves and failure strain at different binder content and different curing time, (b) assessing the effect of binder content and binder type on unconfined compressive strength (UCS), (c) analyzing quantitatively the relationships of failure strain–UCS and deformation modulus–UCS to predict approximately one parameter by using the other one, and (d) analyzing some observations on the change in microstructure of solidified sediments.

## 2. Materials and methods

### 2.1. Materials

The marine sediments studied in this research were dredged from East Port of Dunkirk harbor in France. The samples were collected by a cutter suction dredger in sufficient quantity to complete all the tests. The test results of the physical characterization of sediments are shown in Table 1. The sediment is classified as silt of high plasticity (MH) with organics (>3%) according to the Unified Soil Classification System. The dredged sediments have high initial water content (>value of liquid limit) and low absolute density (<2.65–2.70 g/cm$^3$ of typical range of soils). The plasticity index of 40.8% permits to consider the studied sediments as high compressible soils.

**Table 1**
Physical properties of sediment sample.

| Parameters | | Values |
|---|---|---|
| $\omega_i$ (%) | | 129.9 |
| $\rho_s$ (g/cm$^3$) | | 2.53 |
| LL (%) | | 76.1 |
| PL (%) | | 35.3 |
| PI (%) | | 40.8 |
| Methylene blue value (g/100 g) | | 3.1 |
| Organic matter content (%) | | 6.27 |
| Particle size distribution (%) | Grain size < 2 μm | 14.5 |
| | 2 μm < grain size < 63 μm | 74.7 |
| | Grain size > 63 μm | 10.8 |

The cement used to solidify sediments is denoted CEM I 42.5R HSR, which was produced in Belgium. In terms of chemical components, the cement contains 63.3% CaO, 21.4% $SiO_2$, 4.0% $Fe_2O_3$, 3.3% $Al_2O_3$, 2.4% MgO and other components. The specific gravity of cement grains is 3.17.

The used fly ash is classified as class F fly ash, collected from a power plant in France. The main chemical components of fly ash include 50.0% $SiO_2$, 8.5% $Fe_2O_3$, 29.0% $Al_2O_3$, 4.5% $K_2O$, 3.0% MgO and less than 1.0% CaO.

The lime used in this study contains mainly more than 90% CaO and less than 2% MgO. The specific gravity of lime grains is 3.18.

Tap water was used for modified Proctor compaction tests and molding specimens for unconfined compressive strength tests. Based on these materials, the designed mixes are reported in Table 2.

### 2.2. Methods

The sediments were pretreated before the preparation of cylindrical specimens. The pretreatment of sediments including decantation, drying and grinding is shown in Fig. 1. 156 cylindrical specimens with 50 mm in diameter and 100 mm in length were prepared for unconfined compression tests, by using maximum dry density and optimum moisture content defined by modified Proctor compaction tests. It was found to be important to add the tap water into sediments prior to adding the binders during the mixing process to provide homogeneous mixtures. The binders such as cement, lime and fly ash were then added and mixed together with wet sediment for about 3 min by a mechanical agitator. Note that the amount of binder was calculated on the total mass of dry soil plus binder. Visual examination of mixed specimens is necessary to guarantee the mixtures to be satisfactorily homogeneous. Three small portions of each mixture were taken to determine water content, and the difference between calculated water content and optimum water content should be within $\pm 0.5\%$.

After mixing mixtures, the cylindrical specimens were statically compacted inside a cylindrical split steel mold. The specimen was immediately extracted from the lubricated steel mold after molding process, and the weight and dimension were measured with accuracies of 0.01 g and 0.01 mm. The samples were placed within sealed plastic sample containers to avoid moisture change with surrounding air. They were cured in a curing room at 20 ± 1 °C and relative humidity of 98% for 14, 28, 60 and 90 days. It is important to note that the

**Table 2**
Designed mixes on sediments and binders.

| Mixes | Sediment (%) | Lime (%) | Cement (%) | Fly ash (%) | Optimum water content (%) |
|---|---|---|---|---|---|
| SD | 100 | – | – | – | 21.6 |
| SD3L | 97 | 3 | – | – | 23.3 |
| SD6L | 94 | 6 | – | – | 23.8 |
| SD9L | 91 | 9 | – | – | 23.9 |
| SD3C | 97 | – | 3 | – | 20.9 |
| SD6C | 94 | – | 6 | – | 20.7 |
| SD9C | 91 | – | 9 | – | 20.4 |
| SD3L3CV | 94 | 3 | – | 3 | 21.9 |
| SD3L6CV | 91 | 3 | – | 6 | 20.8 |
| SD6L3CV | 91 | 6 | – | 3 | 22.3 |
| SD3C3CV | 94 | – | 3 | 3 | 20.7 |
| SD3C6CV | 91 | – | 3 | 6 | 20.8 |
| SD6C3CV | 91 | – | 6 | 3 | 20.4 |

C: Cement, L: Lime, CV: Fly ash.