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Shear strength performance of marine sediments stabilized using cement, lime and fly ash

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HIGHLIGHTS

- Direct shear test and mineral elemental analyses are carried out on sediment mixture stabilized using cement, lime and fly ash.
- Chemical stabilization increases sample cohesion but affects friction angle significantly less.
- The ratios of Al and Si for sediment samples stabilized using both lime and cement are improved depending on curing times.
- Fly ash causes the refinement of pore structure followed by pozzolanic reaction.
- Statistical analysis demonstrates that the sediment elemental ratio does improve significantly the gain in cohesion.

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ABSTRACT

The combined effects of the chemical stabilization of sediments using lime, cement and fly ash on the sediment shear strength behavior are studied for geotechnical purposes. An elemental analysis is carried out to examine the chemical aspects of stabilized sediments resulting from a series of chemical reactions. Direct shear strength measurements are performed to investigate shear strength improvements and stress-strain behavior of mix samples. A statistical analysis using the principal component analysis and the ANOVA (ANalysis Of Variance) method is also conducted to examine the correlation between cohesion and elemental ratio resulting from the chemical reactions. The analysis of the principal components suggests that Ca and Si and Al and K have greater impact on cohesion than the other elements. However, the ANOVA method reveals that the elemental ratios of Si, Al and Ca produce less impact on the sediment overall gain in cohesion at 28 days of curing. These results demonstrate that the gain in cohesion mostly depends on some other physical parameters, which need to be yet examined. The prediction equation of the cohesion indicates each elemental component gain weight on the overall cohesion gain resulting from the chemical reactions. In short, the considered equation still needs to be refined, notably in terms of performing further laboratory testing.

1. Introduction

The production of dredged sediments in France is about thirty-five to forty million cubic meters annually. 90% of the dredged sediments are discharged into the sea and might cause a long-term change of the marine environment with significant impact on aquatic fauna and flora.

The possibility to reuse dredged sediments for road and building construction has already been studied by many authors [11,32,3,21]. However, several fundamental questions remain and need to be clarified. The present study is conducted to analyze gain in shear strength of dredged sediments combined with fly ash and hydraulic binders. Dredged sediments in their natural state lack the strength, the dimensional stability and the durability required for geotechnical materials used for building and road construction.

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Nevertheless, these inherent deficiencies may be overcome through stabilization by mechanical compaction and addition of chemical stabilizer agents such as lime, cement or fly ash and other type of binders. The technique that modifies the weak characteristics and properties of soil is called soil stabilization. According to Ingles and Metcalf [13], soil strength and compressibility can be improved by physical or chemical stabilization. In physical stabilization, the characteristics and properties improve thanks to soil densification by the addition of other soils with different grain size distribution or by applying higher compaction rate. On the other hand, in chemical stabilization, the soil structure changes thanks to the chemical interactions between soil particles and chemical additives. Little and Nair [18] have demonstrated that soil stiffness, workability and swell characteristics become appropriate when active compounds are added.

The most common additives used for chemical stabilization are lime and ordinary Portland cement. In many countries, lime is recommended to stabilize clayey soils and clays because of a texture change and a plasticity reduction due to the chemical interactions between soil and lime take place. Lime is the result of the calcination of limestone and/or carbonate rocks. According to Thompson [33], the chemical reaction between lime and soil starts immediately after mixing and continues long after. Lime chemical reactions can be divided into four categories: cation exchange, flocculation and agglomeration, carbonation and pozzolanic reactions. Adding lime to soil increases free calcium cation, which might then replace weaker metallic cations adsorbed in colloidal surfaces. These reactions reduce DDL (Diffuse Double Layer) size in clay particles, resulting in a closer arrangement of particles, i.e., flocculation increases [33,35,20]. Pozzolanic reactions take place slowly and occur between soil silica and/or alumina in a favorable environment pH (about 12), forming cementitious compounds like hydrated calcium silicates (CSH) and aluminates (CAH).

Portland cement is often used for the chemical stabilization of granular soils. Walker [37] proposes a systematic investigation of the properties of cement stabilized soils and demonstrates that Unconfined Compressive Strength (UCS) increases with the cement amount increase but is hindered by a clay content with a plasticity index (PI) higher than 15. Cement hydration produces four typical compounds: tricalcium silicate (C3S), dicalcium silicate (C2S), tricalcium aluminate (C3A) and tetracalcium iron-aluminate (C4AF). Curing time and cement amount are responsible for the improvement in the soil-cement properties (i.e., increase in cohesion, bearing capacity, unconfined compression and tensile strength) [28,30,27]. Huang et al. [12] address the problem of the cement bonding strength of stabilized dredged materials after crushing and compaction. It appears that the strength of a stabilized dredged material decreases when it is crushed and compacted. The stabilized dredged material structure is destroyed by crushing and a new soil body (or structure) is formed by the compaction effort. This result shows that the structure of stabilized dredged materials is driven by the cement hydration effect.

In the last decades, fly ash has been successfully used as soil additive as well. Fly ash is a byproduct of coal-fired electrical power plants and contains different mineral compounds such as: silicon dioxide (SiO_2), aluminum oxide (Al_2O_3) and calcium oxide (CaO). Replacing cement by fly ash could dramatically reduce carbon dioxide emissions from the cement industry. Specifically, the pozzolanic addition of waste byproducts such as fly ash or paper sludge ash are considered to be environmentally friendly and sustainable [36], Goni et al. [8], Ferrandiz-Mas et al. [6]. Fly ash exhibits pozzolanic behavior, which can vary depending on original coal and burning processes. Generally, fly ash is classified in C or F categories. C fly ash has a high CaO content (about 20%) that induces some pozzolanic reactions and self-cementing properties. In F fly ash, the CaO content is lower (about 7%) and, thus, only the pozzolanic reactions occur. To ensure self-cementing in F fly ash, quicklime, hydrated lime and/or Portland cement are added [23,19]. Erdal [4] proposes an evaluation of the effects of the addition of class C fly ash, lime and cement on expansive soil. The results show that the addition of 20% fly ash decreases the swelling potential to nearly the swelling potential obtained with an 8% lime addition. With the addition of 20% to 25% fly ash, there is only a slight decrease in the swelling potential of expansive soils, indicating that the optimum fly ash content is around 20%. Li and Benson [17] also confirm the mechanical performance improvement of road-surface gravel and recycled asphalt pavement (RAP) stabilized using fly ash. Kang et al. [15] have shown that the addition of lime kiln dust and fly ash in soft clays enhances performances, as demonstrated by the increased specific gravity, unconfined compression strength (UCS) and resilient modulus (RM). They conclude that the long-term strength gain can be attributed to pozzolanic reactions occurring with the slow consumption of $Ca(OH)_2$ and short-term strength gain to cation exchange. Trivalent and bivalent cations (Al^{3+} and Ca^{2+}) found in fly ash are attracted by the clay particles through cation exchange and replace lower valence cation (H^+, Na^+, K^+).

The improvement of soil properties by chemical stabilization also depends on the (i) soil material characteristics like soil particle size, chemical composition, ion content in pore water, organic matter and (ii) stabilizer material such as stabilizer amount and water/stabilizer ratio, (iii) mixture design and (iv) on the treatment conditions such as curing time and special treatments corresponding to each local environment.

The literature review for this paper reveals that soil strength improvement is mainly addressed through unconfined compressive testing. This is because soil overall strength can thus be measured easily and at low cost. However, little research is focusing on the strength gain due to shear strength improvement. Sediment shear properties subjected to chemical stabilization are also relevant because shear strength is a key parameter for geotechnical applications and design such as dyke or dam. The objective of the present study is to examine lime, cement and fly ash effects on the improvement of the mechanical characteristics of stabilized sediments using direct shear testing and elemental analysis of stabilized sediment samples. In addition, a statistical analysis is conducted to determine the correlation between the elemental mineral components and cohesion gain.

2. Materials and methods

The Dredged Sediments (DS) from the la Baule le Pouliguen Harbor are characterized according to the French recommendations for embankments and pavement constructionGuide des Terrassements Routier [9] . The results show that the present dredged sediment can be classified as silt clayey with liquidity and plasticity limits equals to 55% and 41%, respectively, and a plasticity index of 14% (Table 1).

Table 1
Geotechnical properties of the marine sediment.

Sand (>63 μm), (%)	36
Silt (2–63 μm), (%)	31.5
Clay (<2 μm), (%)	32.5
Initial water content (%)	153
Methylene blue value	2.75
Specific gravity (Mg/m^3)	2.7
Liquid limit LL (%)	55
Plasticity limit PL (%)	41
pH	8.5
Conductivity (ms/cm)	11.5
Salinity (g/kg)	6.7
Total dissolved solids (g/l)	6.4
Organic content (%)	12.1
Carbonate content (%)	26