Valorisation of marine sediments with novel eco-friendly OPC-CSA composite binder

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Abstract As an eco-friendly binder, ordinary Portland and calcium sulfoaluminate (OPC-CSA) composite binder are innovatively introduced in the Stabilization/solidification (S/S) of dredged marine sediments waste from Dunkirk harbour in France. This study scrutinizes the feasibility of using OPC-CSA composite binder for the S/S treatment of marine sediments waste as road construction materials, in terms of a series of modified Proctor compaction, immediate Californian Bearing Ratio (I-CBR) index, unconfined compressive strength, splitting tensile strength, and elastic modulus tests. The obtained experimental results show that the compaction, bearing capacity and mechanical performance of the OPC-CSA composite binder solidified sediments is significantly improved, as compared with the raw sediments and OPC/CSA single binder treated sediments. These parameters are highly dependent on the ratio of OPC/CSA, binder content and curing time. Especially, OPC played a significant role in developing the final mechanic performance, while CSA mainly promotes early- mechanical properties development. Therefore, the lab-scale experiment demonstrates that OPC-CSA composite binder could be considered as a green and high-performance binder for the S/S treatment of marine sediments waste in comparison to OPC.

Keywords Sediments valorisation/recycling, Ordinary Portland Cement, Calcium sulfoaluminate cement, Road material.

I. INTRODUCTION

With the rapid growth of urbanization and industrialization, many activities of river-way, port construction and maintenance are carried out each year, which produce a huge volume of dredged sediments [1]. Therefore, faced with such a huge volume of sediments waste, the scientific and reasonable method of sediments management is mandatory to diminish the potential environmental risks. Stabilization/solidification (S/S) is a popular method for the treatment of sediments.

Ordinary Portland Cement (OPC) is a widely used binder for S/S, owing to its ease of availability, inexpensive, and reliable. The available extensive literature has widely reported the excellent performance of OPC in the S/S treatment [2]. In addition, it has reported that about 5-7 % of anthropogenic CO_2 emission is due to OPC manufacturing [3]. Therefore, there has been increasing research interest in alternative low-carbon green cementitious materials to replace current mainstream OPC binder.

Recently, Calcium Sulfoaluminate (CSA) cement have emerged as a sustainable alternative to Portland cement. CSA cement is produced by the calcination of gypsum, bauxite, and limestone at ~1250 °C. The process reduces the CO_2 emission as compared to OPC production, which is carried out at ~1450 °C [4]. OPC-CSA composite binder have been used to improve flexural and compressive strength by combining each advantage. The strength of OPC-CSA composite binder, depending on the OPC and CSA cement proportion, the suitable ratio of OPC and CSA can lead to higher early and long-term strength of OPC-CSA composite binder [5]. However, these studies were based on OPC-CSA paste, mortar, and concrete. So far, to the best of the author's knowledge, the effects of OPC-CSA composite binder for the geotechnical properties, especially S/S treatment of dredged sediments has not yet been reported. The performance of OPC-CSA composite binder in the treatment of dredged sediments is not yet clear. Therefore, this study evaluates the effectiveness of eco-friendly OPC-CSA composite binder-treated the marine sediment from Dunkirk Port (France) as road material.

II. Materials and methodology

2.1 Materials

The studied sediments (SD) were dredged from Dunkirk Harbour in the north of France. The dredged marine sediments were naturally dewatered firstly, then removed and stored in barrels at the laboratory.

Table 1 shows the basic physical characteristics of marine sediments and corresponding France and/or Europe standards used in this study. In terms of binders, Ordinary Portland Cement (OPC) with CEM I 52.5 R from LafargeHolcim Saint-Pierre-La-Cour Company and Calcium Sulfoaluminate cement (CSA) from Vicat Company were used in this study. The two major mineralogical elements of OPC were 63.74 % C3S and 18.04 % β-C2S, meanwhile, CSA contained 45.45 % C4A3S̄ and 26.11 % β-C2S.

TABLE 1. **Basic physical characteristics of Dunkirk sediments.**

Parameter	Value	Test standard
Initial water content (%)	5.20	NF P 94-050
Specific gravity	2.58	NF EN ISO 17892-3
Organic contents (%)	7.67	XP P94-047
Methylene Blue Value (g/cm^3)	0.79	NF P94 068
Liquid limit (%)	39.5	EN ISO 17892-12
Plastic limit (%)	28.0	EN ISO 17892-12
Plasticity index (%)	11.5	EN ISO 17892-12
Clay fraction (% < 2 µm)	6.97	EN ISO 13320
Silt fraction (2 µm < % < 63 µm)	39.48	EN ISO 13320
Sand fraction (% > 63 µm)	53.55	EN ISO 13320

2.2 Experimental program

The experimental program includes two groups of mixes, group I where OPC/binder ≥ 50% and group II where CSA/binder ≥50 %. This choice is made after a previous research work performed [6]. It should be noted that the content of OPC and CSA was determined in percentage by mass of dry sediments. Tap water was used as mixing water.

TABLE 2. Mix proportions of different samples.

		Group I			Group II		
Samples	SD	SD2P2C	SD4P2C	SD6P2C	SD2C2P	SD4C2P	SD6C2P
OPC (%)	0	2	4	6	2	2	2
CSA (%)	0	2	2	2	2	4	6

The procedures to undertake the modified Proctor compaction tests and the measurements of immediate Californian Bearing Ratio (I-CBR) were performed according to the standard NF EN 13286-2 and NF EN 13286-47. It should be noted that the dry sediments and water were mixed by a planetary mixer, and then placed in a room at 20 ℃ for 24 h. All the compaction and I-CBR tests shall be carried out no later than 90 min after mixing prepared wet sediments with binders. After modified Proctor test, the compacted specimen was loaded with a cylindrical plunger of 50 mm in diameter at a constant speed of 1.27 mm/min. The preparation of cylindrical specimens (D=50 mm, H=100 mm) for unconfined compressive strength (q_c), elastic modulus (E), and indirect tensile strength (q_{it}) tests were undertaken according to NF EN 13286-53. The compacted specimen was demoulded and stored in covered plastic boxes, then placed in a curing room at 20 ℃ for 3 d, 7 d, and 28 d. The unconfined compressive strength and indirect tensile strength were carried out with an INSTRON 5500 R 4206-006 testing machine according to NF EN 13286-41 and NF EN 13286-42, respectively. The elastic modulus is determined in an unconfined compression test in accordance with NF EN 13286-43. In this later, the secant slope at 30 % of peak compressive strength is used to evaluate the elastic modulus. The results discussed later of each mix were the average values measured on three specimens.

III. Results and discussion

3.1 Proctor compaction test

Fig. 1 (a) and (b) illustrates the Maximum Dry Density (MDD) and corresponding Optimum Moisture Content (OMC) of treated sediments with the various percentages of OPC (P) and CSA (C). From the obtained results, it appears that the effect of OPC and CSA is equivalent in terms of MDD changes. In comparison to untreated sediment, the MDD is improved with the addition of 4% of binders (SD2P2C), then the MDD decrease for 6% treatment (SD2P4C and SD4P2C) before increasing again to reach the observed value for untreated sediment for 8% treatment (SD2P6C and SD6C2P). In terms of OMC variation, in parallel to the increase of MDD a decrease of OMC is obverse and vice versa.

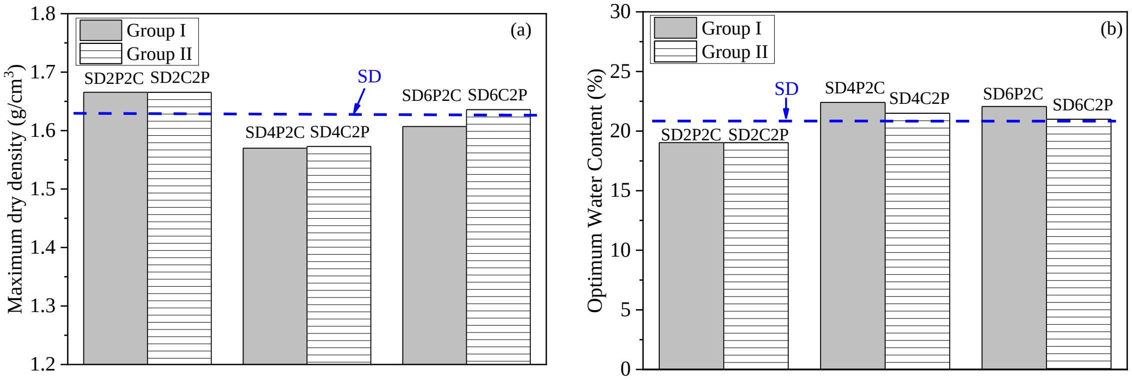


FIGURE 1. **(a) Maximum dry density; (b) Optimal moisture content.**

3.2 Immediate California Bearing Ratio (I-CBR) test

Fig. 2 summarises all the I-CBR index values at the optimal moisture contents of treated sediments. The results of OPC/CSA single cement solidified dredged sediments specimens SD6P and SD6C from our previous study [6], are added in Fig. 2 for comparison. In comparison to untreated sediment, all the I-CBR values are improved with treatments. It is notable that all the I-CBR index values of the OPC-CSA treated sediments are higher than the prescribed value to the use in the foundation layer (I-CBR ⩾ 35 %). Even the I-CBR index values of SD4C2P and SD6C2P are complied with the standard requirement of the use as base layer (I-CBR ⩾ 50 %), according to the French Standard [7]. Regarding the effect of OPC and CSA on the I-CBR values, from the obtained results it appears that the impact of OPC addition is higher than that of CSA addition. As an example, for the binders which contain 2% of CSA and an increasing amount of OPC (2%, 4% and 6%), the I-CBR values increase from 35% to 40%. For the mixes with a binder composed of 2% of OPC and an increasing amount of CSA (2%, 4% and 6%), the I-CBR values increase from 35% to 55% and then to 60%.

It is interesting to note, that the combination of OPC and CSA as low as 2% (SD2P2C) allows reaching an I-CBR of 35%. It is also to note that the impact in terms of carbon dioxide emission in the production of OPC or CSA is quite different. The carbon dioxide emitted solely from the chemical reaction during the production of OPC and CSA is in the ratio of 2.6. This allows concluding that about 30% of carbon dioxide emission is saved each time a combined binder (OPC and CSA) with a ratio of 1 is used. For the higher amount of binders (6% of binders), the combination of OPC and CSA allow probably to reduce the impact of CO_2 emission by more than 40%.

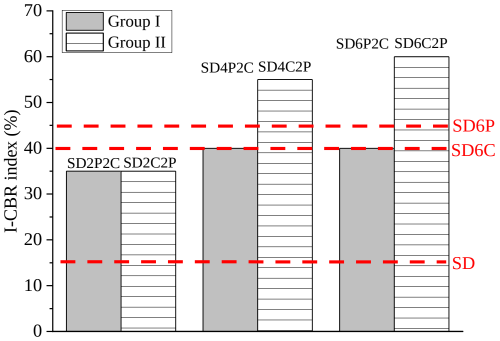


FIGURE 2. **I-CBR index of solidified sediments with OPC-CSA composite binder.**

3.3 Unconfined compressive strength

The unconfined compressive strength (q_c) of the OPC-CSA composite binder solidified dredged sediments is shown in Fig. 3. The q_c of OPC/CSA single cement solidified dredged sediments (SD6P and SD6C) at 28d are illustrated in Fig. 3, as a reference from the previous study [6]. It could be observed that q_c of all the treated sediments is significantly enhanced compared with untreated sediment SD. After the addition of 2 % OPC and 2 % CSA (SD2P2C/SD2C2P), the q_c of the treated sediments at 3 d is 1.29 MPa, 158 % higher than that of the SD specimen. Besides, q_c of all the treated sediment increased with the increase of total binder content and curing time, which can be explained by the increasing of formed hydration product of binders with the increasing of binder content and curing time.

For the SD6P specimen, the addition of 2 % CSA (SD6P2C) can importantly increase the compressive strength. Even the SD6P2C specimen at 3 d showed a higher compressive strength, which was 14 % higher than the value of SD6P at 28 d. Besides, q_c of SD4P2C specimen at 7 d is comparable to that of SD6P specimen at 28 d, whereas the q_c of SD4P2C specimen at 28 d is relatively high. Therefore, the incorporation of CSA has a positive effect on the compressive strength of OPC-treated sediments; the incorporation of CSA may promote OPC-CSA reaction progress and early-strength development of treated sediments. By contrast, compared to SD6C specimen at 28 d, SD2C2P and SD4C2P specimens presented similar strength at 28 d, achieved 95 % and 102 % of the SD6C specimen strength, while the q_c values of SD6C2P at 3 d achieved 127 %. This verified that the incorporation of OPC enhanced q_c of CSA-treated sediments.

Based on the above results, it is undoubted that the incorporation of both OPC and CSA presented favourable strength contribution for OPC-CSA composite binder solidified sediments. Especially, OPC played a significant role in developing the final compressive strength, while CSA mainly promotes early-strength development.

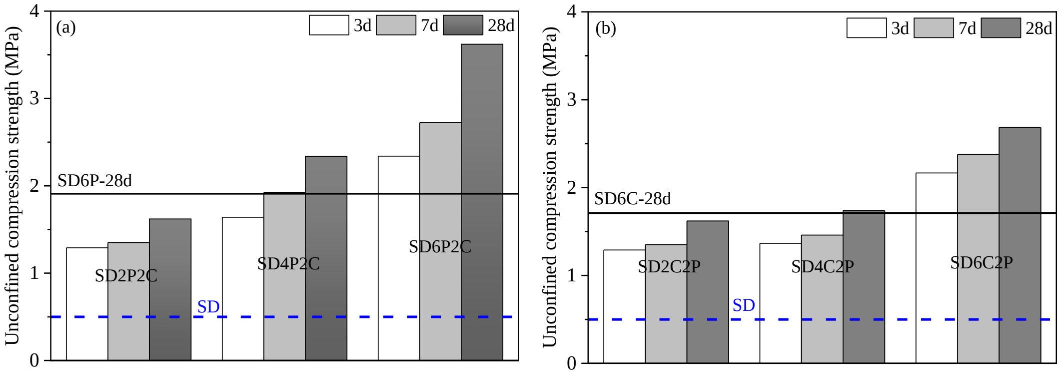


FIGURE 3. Unconfined compressive strength of solidified sediments (a) Group I; (b) Group II.

3.4 Elastic modulus

Fig. 4 exhibits the elastic modulus of all the treated sediments specimens at 3, 7, and 28 d. The SD6P and SD6C reported by previous research [6] are also plotted in Fig. 4 as control specimens. In Fig. 4 (a), the variation in the elastic modulus has an upward trend as the increase of binder dosage, the ratio of OPC/binder, and the curing time. Especially, the CSA-incorporated OPC treated specimens SD4P2C had comparable 7d-E value to that of the 28d-control specimen SD6P, and it is stronger than the control specimen SD6P after 28 d curing. A similar conclusion can be observed in Fig. 4 (b), for group II specimens, all the binder dosage, ratio of CSA/binder, and curing time had a great influence on the elastic modulus. By comparison, the inclusion of OPC in CSA-treated sediments enhances the elastic modulus significantly. It is clear that in Fig. 4 (b), the E values of SD2C2P and SD4C2P specimen at 3 d is about 76 % and 109 % that of SD6P control specimen at 28 d.

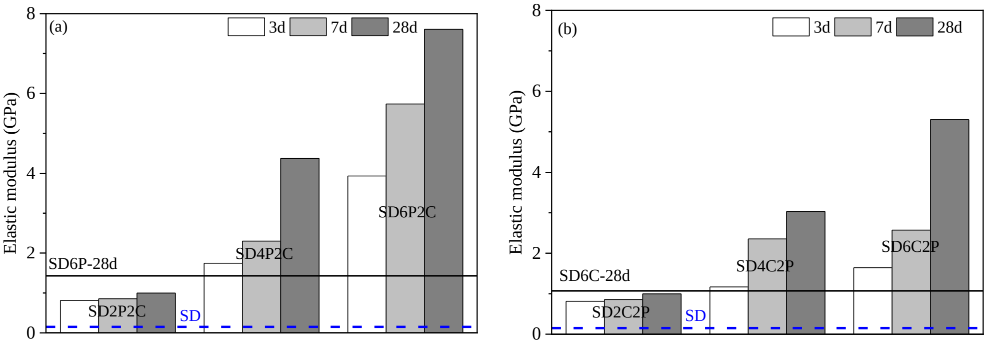
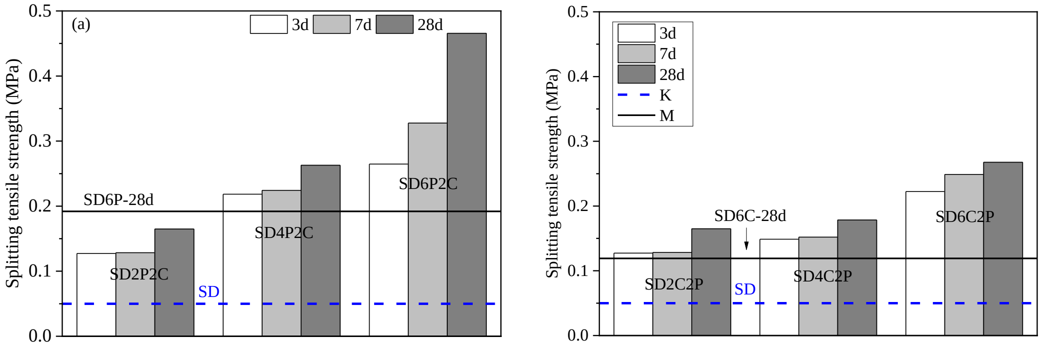


FIGURE 4. **Elastic modulus of solidified sediments (a) Group I; (b) Group II.**

3.5 Splitting tensile strength

Fig. 5 illustrates the effects of OPC-CSA composite binder on the splitting tensile strength (q_{it}) of solidified sediments. It is evident that SD displays the lowest q_{it} value (0.050 MPa). And all the OPC-CSA solidified sediments show a higher q_{it} than that of SD.

By comparison, the inclusion of CSA in OPC-treated sediments enhances not only the early splitting tensile strength but also the late one. For example, the q_{it} of SD4P2C specimen at 3d is higher than that of SD6P control specimen at 28d. Even for the low binder dosage specimen SD2P2C, the q_{it} at 28 d could reach to 86 % of that of the SD6P control specimen at 28 d. Furthermore, it can be clearly seen it that the low binder dosage specimen SD2C2P at 3d possess stronger splitting tensile strength in comparison with that of the SD6C control specimen at 28 d. These results could be also confirmed that OPC-CSA composite binder has an excellent performance than OPC/CSA single cement, in improving the splitting tensile strength of solidified sediments.



(a) **(b)**

FIGURE 5. **Splitting tensile strength of solidified sediments (a) Group I; (b) Group II.**

3.6 Evaluation of solidified sediments as road materials

The main objective of this study is to evaluate the ability of using OPC-CSA composite binder in improving the mechanical characteristics of Dunkirk sediments in order to be used as a sub-base or base course material in the road construction. The ability of the use of the material in this field is deduced from the mechanical characteristics (typically the direct tensile strength and the elastic modulus) measured after one year and regarding the classification in specific diagram as shown in Fig. 6. For practical application, the direct tensile strength is measured through the indirect tensile (splitting tensile) strength test. To deduce the direct tensile strength, Equation 1 as mentioned in the European test standard NF EN 14227-15 is used. Moreover, the mechanical characteristics are generally evaluated after 28 days. The measured values at this issue are used to predict the mechanical characteristics of the specimens at 360 days using Equation 2 and Equation 3.

$$q_t = 0.8 * q_{it} \qquad (1)$$

$$(q_{t\text{-}28d})/q_{t\text{-}360d}) = 0.6 \qquad (2)$$

$$(E_{\text{-}28d})/E_{\text{-}360d}) = 0.6 \qquad (3)$$

The predicted values for all the mixes are reported in Fig. 6. For comparison, the results of untreated sediment SD and OPC/CSA single binder treated specimens SD6P and SD6C [6], are also reported on the same figure. According to the classification, it can be found that a great improvement of material classification can be observed, compared with SD, SD6P and SD6C. This proves the beneficial effects of OPC-CSA composite binder than OPC/CSA single cement treatment to increase the mechanical properties of raw sediments. It should be noted that only SD6P2C specimen belongs to the class T2, this means that only SD6P2C specimen in this study can be used as a sub-base or base course material for a large class of traffic intensities. All the specimens (SD2P2C, SD4P2C, SD2C2P, SD4C2P, and SD6C2P) fall within the class T1. Hence, these materials belonging to the class S1 might be possibly reused as roadbed filling materials for roads of low traffic intensity.

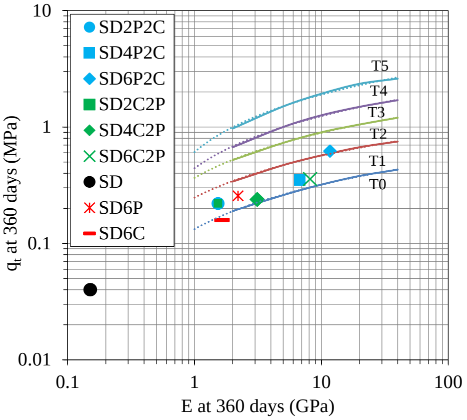


FIGURE 6. Classification of solidified sediments with OPC-CSA composite binder.

IV. Conclusion

In this study, the novel eco-binder, ordinary Portland and calcium sulfoaluminate composite binder, was the first time introduced for stabilization/solidification (S/S) of marine sediments waste. Based on the experimental results, the following conclusions can be drawn.

(1) Compared with the raw sediments and OPC/CSA single binder treated dredged sediments, the compaction and bearing capacity performance of the OPC-CSA composite binder solidified sediments is significantly improved. However, group II specimens with a high CSA/binder ratio have better performance of the I-CBR index.

(2) The incorporation of OPC-CSA composite binder in sediments waste is effective for the improvement in mechanic behaviour of solidified sediments than OPC/CSA single binder treated, includes compressive strength, tensile strength and elastic modulus, and these mechanical parameters are highly dependent on the ratio of OPC/CSA, binder content and curing time. Especially OPC played a significant role in developing the final mechanic performance, while CSA mainly promotes early-mechanic development.

(3) The OPC-CSA composite binder could be considered as a green and high-performance binder for the S/S treatment of marine sediments waste in comparison to OPC. The S/S experiment further confirmed that OPC-CSA composite binder treated sediments specimens fulfilled the requirements of bearing capacity performance and mechanical strength for road on-site reuse.

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