Self-compacting Backfills using Fly Ash and Dredged Marine Sediments for Public Work Applications

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Abstract

Sediment accumulation at the bottom of ports disrupts maritime activities and disturbs the physicochemical balance of water bodies. In France, the maintenance of the 6500-kilometer long coastline would require the extraction of about 50 million m^3 of marine sediments every year. For several years, these sediments were considered waste. However, they are increasingly being acknowledged as a resource in need of management. Several research studies were conducted to find valorization ways that satisfy technical and regulatory requirements. These sediments present interesting heterogeneous physicochemical, mineralogical, and geotechnical characteristics. However, they may contain contamination, which could limit their uses. This paper deals with the possibility of producing self-compacting backfills using dredged marine sediments, fly-ash, and hydraulic binders for public work applications. The impact of dredged sediments on the composition of self-compacting backfills was studied. Moreover, the impact of fly ash and binder type and percentage on the backfill behavior and mechanical properties was discussed.

Keywords: Sediment; Valorization; Sustainable materials; Backfill; Waste management

1. Introduction

The accumulation of sediments in ports for several years causes capacity- and efficiency losses, which emphasize the importance of sediment dredging management in the world. For example, the European countries generate sediment-dredged volumes of 100 and 200 million cubic meters per year (Maherzi et al., 2018). Placing dredged sediments in landfills, which is expensive, is only practiced when there are no other solutions (Maherzi et al., 2018). However, dredged sediments can be considered as alternative resources rather than waste (Brahim et al., 2022). With the current limited availability of high-quality aggregates, using dredged sediments as a construction material can optimize their future management (Maherzi et al., 2018).

The suitability of using dredged sediments in lightweight aggregate production has been reported in the literature due to their perpetual availability, homogeneity, and mineralogical and chemical composition (Liu et al., 2018; Ennahal et al., 2021). Dredged sediments have also been used in brick production (Brahim et al., 2022; Slimanou et al., 2019). The replacement of 15% of quartz sand with sediments has resulted in a 63% increase in compressive strength and a 10% decrease in porosity (Ouédraogo et al., 2021). The compressive strength of bricks passed the very strict grade requirements of the American Society for Testing and Materials (ASTM) requirements when 50% of their natural making clay was replaced by dredged sediments (Wang et al., 2018). Ouédraogo et al. (2021) have studied replacing up to 19% of sand with dredged sediments in construction. Benzerzour et al. (2018) have studied mortar compressive strength and weight loss for cement partial substitution of dredged sediments at 5%, 10%, 15% and 20% by mass. The results showed that a 15% substitution of cement by dredged sediments was most suitable for mortars (Benzerzour et al., 2018).

This paper studies the suitability of self-compacting backfill materials using dredged marine sediments, fly-ash, and hydraulic binders for heavy construction applications. The impact of self-compacting backfill composition including type and percentage of fly ash and binder on its physical and mechanical properties is discussed.

Self-compacting backfills are usually injected with pressure to fill cracks, cavities, or ground interstices to improve the mechanical performance and hydraulic characteristics of the soil. In general, backfill stability decreases when its fluidity increases due to water content.

2. Materials and Methods

2.1. Materials

The physicochemical, geotechnical, and mineralogical characteristics of backfill materials are described as follows.

- **Sediments:** The dredged marine sediments were collected from Dunkirk port (France). Table 1 summarizes the sediment physicochemical properties.

Table 1: Sediment physicochemical characteristics

Average water content w (%)	22.35
Average organic content (%)	9.10
Plasticity index PI (%)	13.00
Blue methylene value (g/100g)	2.99
Density of solid grains (t/m^3)	2.44
Grains < 2µm	3.00
2µm < Grains < 63µm	72.00
63µm < Grains	25.00

- **Fly ash:** fly ash, which was taken from Eurovia Harnes site, was composed mainly of silica (SiO_2) and alumina (Al_2O_3). Other elements such as iron oxide (Fe_2O_3/FeO_4) and lime are also present to a lesser extent.

- **Fiber:** Polypropylene fibers are ideal additives in cementitious mixes to reduce plastic withdrawal and cracking and to improve surface properties. The mechanical properties of the fibers that had an average size of 12mm, are shown in Table 2.

Table 2: Polypropylene fibre characteristics

Characteristics	Values
Elastic modulus	3500 – 3900 N/mm^2
Extensibility	320 – 400 N/mm^2
Melting point	160 – 170 °C
Electrical conductivity	0

- **Hydraulic binders:** Three hydraulic binders were used: Cement CEM I 52.5 N, cement CEMI 52.5 PM-ES and Road hydraulic binder RolacPI LH.
  - **ROLAC® PI:** It is a hydraulic binder containing clinker to speed up trafficability after the completion of fills and platforms. The binder ROLAC PI LH consists of more than 60% of lime and 20% of silica dioxide (SiO_2).
  - **Cement CEM I 52.5 N:** This cement is comprised between 95% and 100% of clinker, up to 5% of secondary components, and a small quantity of calcium sulphate to ensure product regularity. The initial setting time, measured at a temperature of 20°C, is greater than 40 min. The density is of about 3.12 g/cm^3, and the compressive strengths, determined based on NF EN 196-1, shows that the compressive strength at 28 days is 62 MPa.
  - **Cement CEM I 52.5 PM-ES:** this cement type is used for concrete products and backfills that would be exposed to aggressive environment, such as maritime environment, zones of marling and water with high sulphate contents, freezing and thawing, and acid medium. The cement produces high-strength concrete after 28 curing days with limited sulphide content.

2.2. Methodology

Several adopted mix designs were optimized for backfill applications, such as trench backfill materials, by improving strength and handling easiness. The essential criteria to satisfy backfill applications are listed below:

- Specimen spread out due to own weight must lie between 350 mm and 500 mm.
- Bearing Capacity Index (IBI) must reach a value of at least 10 within 24 hours to speed up the return to circulation.
- 28-day unconfined compressive strength (UCS) values must lie between 0.5 MPa and 1MPa to ensure material easy handling.
- Slump values must reach at least 15 cm for better drain coating.
- Adequate compressive strength after immersion for better material behavior with water.

Ten mix designs were used to evaluate the impacts of hydraulic binder types and contents on backfill application criteria. The mixes contained 30 % of sediment and 70% of fly ash and cement, respectively. The reference mixture (control) did not contain dredged sediments.

Furthermore, three mix designs containing different type of cement and dredged sediments were tested using a water to cement ratio of 1:2 (W/C=0.5). The dredged sediment percentage was obtained by studying the interaction between sediment and cement.

3. Results and Discussion

3.1. Mechanical study

3.1.1. Sediment and Cement Mix Behavior

Figure 1 shows the variation of the mix mechanical strength with the Sediment / Cement (S/C) ratio. Increasing the (S/C) ratio has adversely affected the mix mechanical properties. Indeed, increasing the (S/C) ratio from 0.2 to 0.8 has decreased the mix mechanical strength by about 67 %, which may be due to the sediment chemical disruptive elements on cement setting such as sulphates and chlorides.

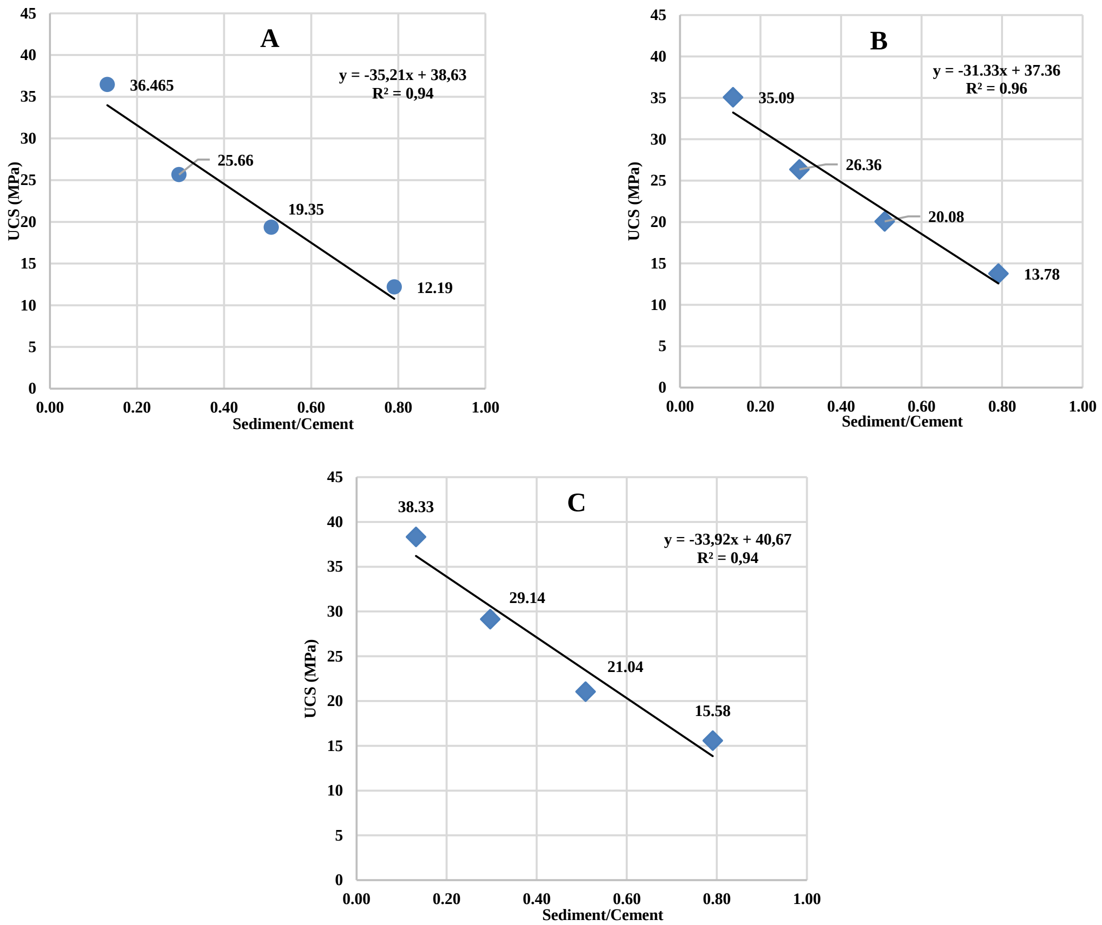

Fig. 1: Mix mechanical strength versus S/C ratios (A: Cement CEM I 52.5 N, B: Cement ROLAC PI LH, C: Cement CEM I 52.5 PM ES)

3.1.2. Abrams Cone Slump

The test, which is defined by standard NF P 18-451, determines four consistency levels according to the slump 10 minutes after pouring. The results presented in Table 3 show that the binder ROLACPI LH gives the best fluidities compared to the other two cements. This can be explained by its low water demand because it is composed of more than 40% blast furnace slag. The formulations were classified according the consistency results.

Table 3: Slump test results

Rate of cement (%)	ROLACPI LH (cm)	CEM I PM (cm)	CEM I N (cm)
6	20.5	18.0	20.0
8	22.0	20.0	24.0
10	24.0	19.5	19.0

3.1.3. Bearing capacity index

The Bearing Capacity Index (IBI) is determined using the following equation:

$$IBI = p/ps \ .100\% \qquad (1)$$

Where p = measured pressure for binders [N/mm^2] and ps = pressure to achieve equal penetration on standard crushed stone [N/mm^2]

Table 4 summarizes the IBI results for the various mixes after 24 and 72 hours. All tested mixes satisfied the fluidity criterion. These results can be attributed to the compactness on granular media composed of 30% sediment and 70% fly ash (Ennahal et al., 2021).

Table 4: Bearing index results for different mixtures

	ROLACPI LH		**CEM I 52.5 PM**		**CEM I 52.5 N**	
Rate of cement (%)	**CBR (24h)**	**CBR (72h)**	**CBR (24h)**	**CBR (72h)**	**CBR (24h)**	**CBR (72h)**
6	26.98	35.58	15.15	32.45	22.76	29.96
8	54.14	64.64	18.30	39.85	22.90	32.30
10	56.50	65.70	23.00	41.81	34.96	44.94

3.1.4. Unconfined Compression Strength

The unconfined compressive strength values (UCS) represent the average of measures taken from three samples. The standard deviation of measurements varied between 0.01 and 0.10 MPa. The compression strength results for the tested samples are shown in Figure 2. They show that increasing cement substitution rates increased the compressive strengths of the tested mixes. It is worth noting that the mixes prepared with cement Rolac PI showed the best mechanical performance compared with those prepared with the cements CEM I 52.5PM and CEM I 52.5 N. This can be explained by the fact that cements containing blast furnace slags are more resistant to chemical elements contained in sediments such as heavy metals, chlorides, sulfates, etc. (Maherzi et al., 2018).

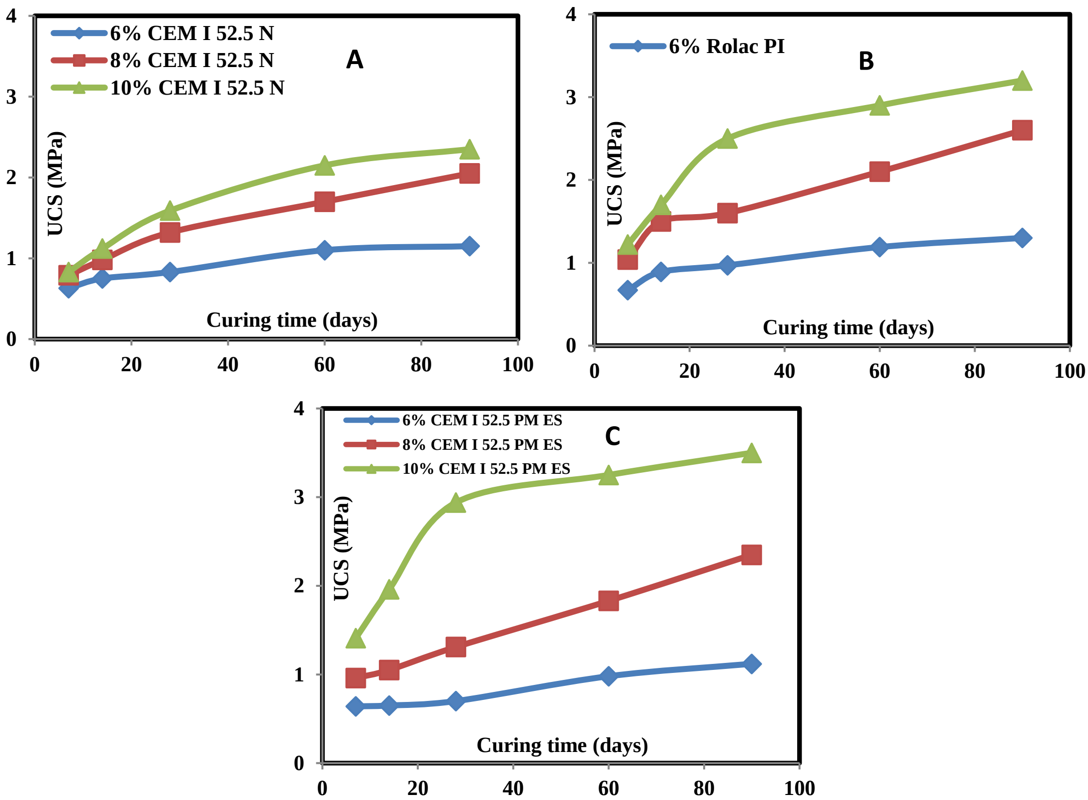

Fig. 2: Compressive strength of various prepared mixes (A: Cement CEM I 52.5 N, B: Cement ROLAC PI LH, C:

Cement CEM I 52.5 PM ES)

3.2. Environmental study

The environmental study was carried out on backfill blocks using the cement ROLAC PI. The blocs were permanently watered and their runoff water was recovered (Figure 3). The runoff water samples, which were recovered after 7, 28, and 60 days, were environmentally analyzed.

Table 5 summarizes the environmental analysis results obtained on the recovered water samples. The environmental analysis results show that the concentration of the leachate environmental elements remain low and did not change drastically with time. Moreover, there were no major changes in the concentrations of the detected elements. Indeed, the use of hydraulic binders prevented the contaminants from the hydration-formed products, which helped mix stability in the short and medium terms.

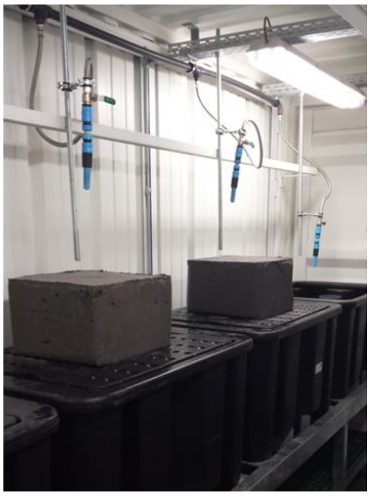

Fig. 3: Grout block leaching test

Table 5: Environmental analysis results

		With sediment			**Without sediment**			**Thresholds of inert waste**	
Analysis	**Unit**	**7**	**28**	**60**	**7**	**28**	**60**		
PAH	µg/l	<1	<1	<1	<1	<1	<1	-	µg/l
PCB	µg/l	<0,07	<0,07	<0,07	<0,07	<0,07	<0,07	-	µg/l
COT	mg/l	3,2	2,8	3,4	3,0	3,0	3,5	-	µg/l
Heavy metals									
Arsenic	µg/l	<5	<5	<5	<5	<5	<5	10	µg/l
Cadmium	µg/l	<0,20	<0,20	<0,20	<0,20	<0,20	<0,20	5	µg/l
Chrome	µg/l	5,9	3,7	2,9	<1	<1	<1	50	µg/l
Copper	µg/l	8,6	<2,0	7,1	5,9	4,6	4,9	50	µg/l
Mercury	µg/l	<0,05	<0,05	<0,05	<0,05	<0,05	<0,05	2000	µg/l
Lead	µg/l	<2,0	<2,0	<2,0	<2,0	<2,0	<2,0	50	µg/l
Nickel	µg/l	<3	<3	<3	<3	<3	<3	20	µg/l
Zinc	µg/l	29	21	10	17	13	11	5000	µg/l

4. Conclusion

The accumulation of sediments at the bottom of ports disrupts maritime activities and disrupts the physicochemical balance of water bodies. For several years, these sediments were considered waste. However, several research studies have been carried out to find ways of valorization that meet technical and regulatory requirements. The research presented in this article examines the suitability of self-compacting embankments using dredged marine sediments, fly ash and hydraulic binders for heavy construction applications. The impact of dredged sediments on the composition of self-compacting embankments has been studied. In addition, the impact of the type and percentage of fly ash and binder on the backfilling behavior and mechanical properties was discussed. According to the results presented above, the following conclusions can be addressed:

1. According to the consistency standard of cementitious materials, the set of self-compacting grouts are qualified as fluid (slump>160mm).
2. The values of the bearing index are greater than 15 after 24 hours of hardening, and greater than 30 after 72 hours of hardening.
3. ROLAC cement comprised of 40% blast furnace slag, has the highest IBI values compared to other cements.
4. After 28 days of normal cure, the self-compacting backfills using ROLAC PI cement had compressive strength values comprising between 0.97 MPa and 2.5 MPa.
5. The results of accelerated environmental monitoring of the tested formulations show the safety of these new materials.

Based on the obtained test results, self-compacting embankments seem to be a promising means of recovery of dredged sediments that meet technical and regulatory requirements.

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