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Reuse of Untreated Fine Sediments as Filler: Is It More Beneficial than Incorporating Them as Sand?

Hamza Beddaa [1,2,*], Amor Ben Fraj [1], Francis Lavergne [1] and Jean-Michel Torrenti [3]

1 Research-Team DIMA, Cerema, 120 Rue de Paris, BP 216 Sourdun, 77487 Provins, France; amor.ben-fraj@cerema.fr (A.B.F.); francis.lavergne@cerema.fr (F.L.)
2 Clamens, Rue des Carrières Z.I. SUD, 77270 Villeparisis, France
3 Gustave Department of Materials and Structures, Eiffel University, 14 Boulevard Newton, 77455 Champs-sur-Marne, France; jean-michel.torrenti@univ-eiffel.fr
* Correspondence: hamzaa.beddaa@gmail.com

Abstract: Large amounts of sediments are dredged each year to ensure navigation. These materials, classified as waste, seem to be promising alternatives to conventional construction materials. Dredging operations, carried out by the Territorial Directorate of the Seine Basin (DTBS), generate an annual volume of sediments of about 150,000 m^3, of which nearly 50% are fine sediments (<80 µm). For these fine sediments, it is necessary to look for possible ways of valorisation, knowing that the coarse sediments, sands and gravels are already easily reused in concrete. The valorisation of fine sediments, such as concrete with 30% sand, has already been evaluated. However, it was found to significantly affect concrete performance; it extends setting time from 3 to 18 h, decreases compressive strength by an average of 50% and increases shrinkage deformation up to 200%. This paper seeks to evaluate the effects of ten different fine sediments, used as substitutes for 10% of cement by volume, on physico-chemical and mechanical properties. The experimental results show that fine sediments marginally affect concrete properties. The main peak of the released heat flux is delayed to less than 4 h, the compressive strength is decreased by 8% on average and the increase in shrinkage deformation does not exceed 17%, except for in two fine sediments. This incorporation method also has an environmental advantage over substituting 30% of concrete with sand, as it reduces CO_2 emissions by almost 10% (instead of 0.2%).

Keywords: untreated sediment; concrete properties; economic viability; carbon footprint

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1. Introduction

Concrete is one of the most consumed materials in the world, which has an effect on the natural material deposits (sand, aggregates, limestone, etc.) that are used directly in the manufacture of concrete. These deposits are becoming increasingly scarce while needs continue to grow. On the other hand, due to modern lifestyles, the progress of industry and technology has led to a significant increase in the amount and type of waste, such as demolition concrete, waste foundry sand and glass. These wastes could be recycled and used as alternative sources of aggregates or cement to produce concrete and meet the challenge of reducing the depletion of raw materials [1–6].

Dredging operations carried out on the waterways of the Paris region generate approximately 150,000 m^3 annually. These sediments require valorisation or storage in waste storage facilities. For inert sediments (86% of the total volume), the main valorisation field is the filling of quarries and ballast. Noninert but nonhazardous sediments are treated before reuse or storage in nonhazardous waste storage facilities (ISDND) [7]. Approximately 190,000 m^3 (25%) of the sediments dredged over the period between 2014 and 2018 were directly stored in Inert Waste Storage Facilities (ISDI) at a cost between 5 and 11 EUR/ton [8] (based on 2012 data; current data may be much higher). For sediment managers, the ISDI sector therefore cost EUR 1 M for these five years (2014–2018). In addition, national and international regulations concerning sediments are increasingly demanding and, thus, in the future, the cost of their current management could be greatly increased.

In recent years, many international studies have been carried out to encourage the valorisation of dredged sediments as alternative materials for civil engineering. These studies indicate various beneficial uses of dredged sediments as raw materials in construction, namely road construction [9–11], cement production [12–19] and the replacement of conventional aggregates for the manufacture of mortar or concrete [20–24]. The sandy fraction (0.08–20 mm) of the Paris region deposit has also shown a potential for reuse as an aggregate in concrete. However, the incorporation of fine particles as a substitute for 30% vol. sand significantly increases the concrete's setting time and total shrinkage as well as decreases the compressive strength by 50% [24]. This concrete was formulated by maintaining a slump that was similar to that of the control concrete. For this purpose, the amount of water added to the mixture was increased with the incorporation of fine sediments. These results are in accordance with those of Millrath et al. [25], who investigated two different methods of mixing: the first one consists of incorporating fine sediments as sand with the same water/cement ratio and the second one is based on keeping the same slump with the incorporation of fine sediments. For the first case, the results of this study showed that as the fine sediment content increases from 0 to 20 wt %, the flow gets reduced by 50% and the compressive strength is slightly affected. However, for the second case, the compressive strength dropped by 50% for a 20% substitution of sand by fine sediments. Therefore, the reuse of fine sediments as sand in concrete offsets any economic or environmental benefits. Nevertheless, their fraction in the deposit is substantial, and it is necessary to find a way to reuse them in concrete (Figure 1; sediments containing more than 40% of fines (<50 μm) represent 70% of the Paris deposit).

Due to their mineralogical and chemical constitution (siliceous, clay, limestone, etc.), sediments could be used to replace the raw materials for Portland cement clinker. Several studies have shown the feasibility and efficiency of this method [12–16]. However, the effective use of fine sediments often requires an adequate thermal treatment process aimed at eliminating the organic fraction and certain pollutants. Van Bunderen et al. [12] studied the hydration of a cement paste formulated with dredged sediments calcined at 865 °C. The results show that treated sediments and fly ash had similar early hydration behaviour. Regarding the mechanical properties, Dang et al. [13] showed that a cement based on calcined sediments (650 and 850 °C for 5 h) develops a compressive strength better than limestone filler but lower than that of the control mortar. These results are in accordance with those presented by Ez-zaki and Diouri [14]. On the other hand, the results reported by Benzerzour et al. [15] showed that the mortar incorporating up to 15 wt % of sediments treated at 850 °C for 1 h develops better mechanical properties than the control mortar. Hadj Sadok et al. [17] also showed that the incorporation of 15% calcined sediments (at 750 °C for 5 h) as a cement substitute improves the compressive strength by 3% at a curing temperature of 40 °C. In the same sense, Safhi et al. [16] showed that the use of up to 20 wt % of treated sediments, at 800 °C for 1 h, in concrete offers a compressive strength comparable to that of the control concrete.

Few studies have been devoted to the valorisation of untreated or just dried sediments. Zhao et al. [19] reported the use of a marine sediment, dried at 40 °C and then ground, as a partial substitute for cement in the manufacture of concretes. Three sediments' contents were used as a substitute for CEM I 52.5 cement (10%, 20% and 30%) to produce concrete. For a substitution of 10 wt % of cement, the slump decreased from 12.5 cm to 9.5 cm and the compressive strength decreased by 6%. Ouédraogo et al. [26] showed that untreated sediments can be used with 300 kg/m^3 (which represents 50% of the binder's total mass) to formulate self-compacting concrete. The results showed that there is no segregation or bleeding in the fresh state, and the compressive strength at 28 days indicates that these sediments can be used for nonstructural concretes.

The sediments' calcination presents several advantages, such as the elimination of a part of the organic matter, the activation of the pozzolanic properties in the long term and the stabilization of the heavy metals. However, this thermal treatment of sediments is costly, both environmentally and economically. For this reason, the valorisation approach of this study is to use the sediments in their raw state. As the sediments of the Seine basin are nondangerous, physical, chemical or thermal treatment is not necessary for the use of the sediments in cement materials. The aim of this paper is to evaluate the effect of using untreated fine sediments as 10% substitutes of cement on concrete properties. This replacement rate is enough to consume the entire deposit in the concrete industry in the Paris region. Concrete samples based on ten different fine sediments are tested to investigate the effect of incorporating fine sediments on the slump, the hydration, the compressive strength and the shrinkage of concrete. The effects of sediment incorporation as filler and as sand on concrete properties, carbon footprint and cost are compared.

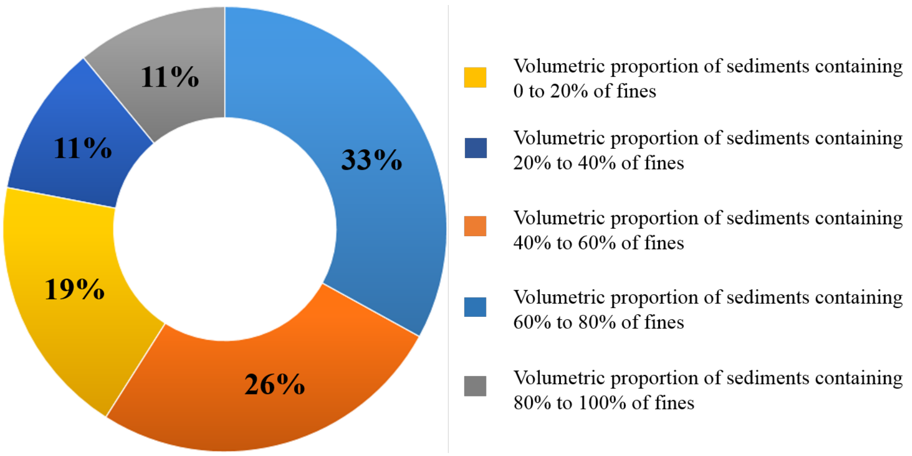

Figure 1. Volume proportion of dredged sediments according to their fines content (<50 µm).

2. Materials and Methods

2.1. Materials

The cement used for this study was a Portland cement type CEM I 52.5 from Calcia plant, which mainly contains clinker (91.3 wt %), gypsum (4.9 wt %) and limestone (3.8 wt %). Regarding aggregates, alluvial aggregates (sand 0/4 mm and gravel 4/20 mm) were used. Their density and water absorption coefficients were respectively 2.41 and 4.7% for sand and 2.53 and 2.32% for coarse aggregates.

For this study, ten sediments from different localities in Seine basin watershed (dredged in 2017) were used. They were collected in the form of sludge and then dried (105 °C) to stabilize the sample's mass and crushed to particles passing through an 80 µm sieve before being characterized and then incorporated into concrete (Figure 2).

Figure 2. Fine sediments dried at 105 °C and crushed (<80 µm).

The total deposit dredged in 2017 by DTBS (Territorial Directorate of Seine Basin) has been characterized [7]. Some dredged sediments were proven to be noninert according to the ISDI threshold, as defined in the decree of 12 December 2014 [27], mainly due to their content of total hydrocarbons (THC) or leached antimony (Sb). A few dredged samples failed to comply with the S1 thresholds, as defined in the decree of 9 August 2006 [27], due to their lead (Pb), zinc (Zn) or mercury (Hg) contents. Additional analyses were therefore necessary to confirm that these sediments were hazardous. Nevertheless, they were still classified as nonhazardous because property HP14, the most important hazard property observed on the waste, was respected. According to Table 1, the content of heavy metals and pollutants in these sediments met ISDI [27] and S1 [28] thresholds. Taking advantage of the strong correlation between Pb, Zn and Hg on the one hand and between leached Sb and HCT on the other hand, which has been proven for the sediments of the Paris region in our previous article [24], these sediments were considered nonhazardous and inert. The sediments' densities, measured by the pycnometer method, varied from one sediment to another, but all dredged sediments were lighter than limestone filler or cement (Table 2).

Table 1. Environmental characterization of sediments.

Parameter	Unit	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	S1	ISDI
Pb	mg/kg	13.9	6.4	1.6	1.1	3.4	15.1	4.5	4.7	10.3	2.6	100	–
Zn	mg/kg	138.5	124.5	121.6	9.2	143.5	228.2	84.5	128.9	163.6	16.1	300	–
Sb (leached)	mg/kg	<0.01	<0.01	0.014	0.017	< 0.01	< 0.01	< 0.01	< 0.01	< 0.01	0.031	–	0.06
PCBs	mg/kg	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	0.135	<0.1	<0.1	0.131	0.68	–
Sulphates	mg/kg	9.8	18.6	9.6	58.4	19.5	16.4	12.4	5.3	<5	55.1	–	1000
Organic matter	%	12.7	6.5	9.9	5.4	14.8	11.9	13.0	13.0	12.9	4.6	–	–

Table 2. Density of different binders.

Sample	Cement	Limestone Filler	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10
Density	3.11	2.70	2.20	2.26	2.24	2.41	2.00	2.26	2.11	2.16	2.16	2.31

2.2. Concrete Mixtures

The control concrete (CC) was C30/37 with good workability, with S4 (16–21 cm) as slump class using a water/cement ratio of 0.55. The study was carried out on twelve concrete mixtures, one with 100% of cement (CC) and eleven with only 90% of cement. In order to ensure the same slump class for all concretes, the substitution of 10% of cement by filler (CF) or by fine sediments (CF1, CF2, . . . , CF10) was carried out by keeping the effective water/binder ratio (binder = cement + fine sediment) and the paste volume (volume of water + volume of fine particles) constant. The water absorbed by the aggregates was measured and therefore added to the mixture. No superplasticiser was added to the mixtures in order to evaluate the real effect of fine sediments. Table 3 indicates the quantities of the different ingredients per 1 m^3.

Table 3. Concrete mixtures (kg/m³).

Concrete Notation	Cement	Limestone Filler	Sediment	Sand (0/4 mm)	Coarse Aggregates (4/20 mm)	Effective Water	Total Water
CC	335.0	0.0	0.0	881.1	814.4	184.3	244.3
CF	301.5	31.7	0.0	881.1	814.4	183.3	243.3
CF1	301.5	0.0	29.0	881.1	814.4	181.8	241.8
CF2	301.5	0.0	29.4	881.1	814.4	182.0	242.0
CF3	301.5	0.0	29.2	881.1	814.4	181.9	241.9
CF4	301.5	0.0	30.2	881.1	814.4	182.5	242.5
CF5	301.5	0.0	27.8	881.1	814.4	181.1	241.1
CF6	301.5	0.0	29.4	881.1	814.4	182.0	242.0
CF7	301.5	0.0	28.5	881.1	814.4	181.5	241.5
CF8	301.5	0.0	28.8	881.1	814.4	181.6	241.6
CF9	301.5	0.0	28.8	881.1	814.4	181.6	241.6
CF10	301.5	0.0	29.6	881.1	814.4	182.1	242.1

2.3. Methods

2.3.1. Fresh Concrete

According to the European Standard EN12350-2 [29], slump values were measured using the Abrams cone for the different mixtures. The unit weight of fresh concrete was measured by means of the weighing of specimens dedicated to the compressive strength tests (cylindrical specimens of 11 cm × 22 cm).

2.3.2. Cement Hydration

The heat released by cement hydration was measured by means of semiadiabatic calorimetry tests (Langavant method), according to the European Standard EN196-9 [30]. A sample of the freshly prepared concrete was poured into an insulated calorimeter. The heat released due to hydration had to be corrected with the calibrated heat loss of the calorimeter, which drove the temperature change. Hence, the heat released by hydration could be estimated using the temperature history once the heat capacity of the sample had been estimated. For this purpose, the temperature was measured every 10 min for 5 days.

2.3.3. Mechanical Strength

The compressive strength tests were carried out according to the European Standard EN12390-3 [31] on cylindrical specimens 11 cm × 22 cm in dimension. The samples were demolded 24 h after being cast, stored in water and then loaded at 3 or 28 days.

2.3.4. Shrinkage Deformation

The mass loss and the total shrinkage strain of the considered concretes were measured on 7 × 7 × 28 cm³ prismatic specimens, according to the French Standard NF P15-433 [32]. The environmental conditions of the storage room were 20 °C and 50% relative humidity. Shrinkage strains were measured, beginning with demoulding at 1 day, by a retractometer calibrated with an INVAR rod before each measurement. The reported shrinkage strains were averaged from three measurements recorded on three different samples of the same concrete.

3. Results and Discussion

3.1. Slump and Unit Weight

Table 4 shows the slump and the unit weight values of the fresh concrete. It appears that the incorporation of fine sediments does not affect the workability of the concrete or slightly improve it. The use of the same volume fraction of the paste, which also has the same w/b ratio, for all concretes could be at the origin of these results. In addition, the presence of humic substances in the sediments can improve the workability of the mixture due to humic substances' plasticising effect [33]. Several studies dealing with the effect of the incorporation of calcined sediments on the rheology of cementitious materials have shown that the substitution of cement by calcined sediments induces a noticeable loss of fluidity, which means that the calcined sediments potentially retain water and therefore the water does not contribute to the fluidity of the mixture [14,18,34].

Unit weight values showed a slight decrease with the incorporation of fine sediments, which is mainly due to the low density of these materials. A similar result can also be found in the literature, which reports that the fresh density of concrete decreases slightly when the substitution of cement with sediments increases, which is also attributed to the lower density of sediments compared to cement [19].

Table 4. Slump and unit weight of different concretes.

	CC	CF	CF1	CF2	CF3	CF4	CF5	CF6	CF7	CF8	CF9	CF10
Slump (cm)	18	20	20	20	20	19	19	19	18	20	20	21
Unit weight (t/m^3)	2.30	2.28	2.24	2.25	2.25	2.28	2.28	2.28	2.28	2.25	2.23	2.26

3.2. Hydration Kinetics

Figure 3 shows that, except for CF5, concrete based on fine sediments reaches almost the same total heat release as the control concrete, per gram of cement. These results highlight that the reactivity of the fine sediments is very low compared to cement. Filler-based concrete also has a heat release comparable to that of most fine sediment-based concrete. Similar results were observed in other studies carried out on calcined sediments. Indeed, these studies showed that the heat released decreases with the increase in the fine sediments content [16,17,35].

The setting delay could be detected by the delay in the appearance of the main peak of the heat flow (Figure 4). The substitution of cement by filler has no effect on hydration kinetics, whereas the incorporation of fine sediments induces a delay, which remains shorter than 4 h. This delay is mainly related to the organic matter present in the sediments, which is partially composed of fulvic and humic acids [36]. These substances can adsorb on cement particles and delay the hydration process [33]. However, the organic matter values shown in Table 1 do not correlate with the produced hydration delays. For example, sediment F3 has the lowest hydration delay, while its organic matter content is more than twice that of sediment F10, which has a higher hydration delay. In fact, without measuring the content of humic substances in a sediment, the total organic matter content does not enable us to predict the effect of organic matter on hydration [37]. The common method used to measure the content of humic substances in aggregates is described in the European Standard EN 1744-1+A1 [38]. Unfortunately, this method cannot be performed on fine sediments, as the sodium hydroxide solution will be absorbed by their fine particles.

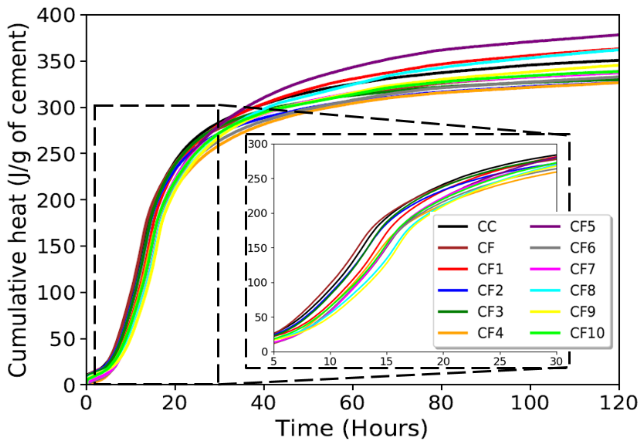

Figure 3. Cumulative heat–semiadiabatic calorimetry tests for different sediment-based concretes.

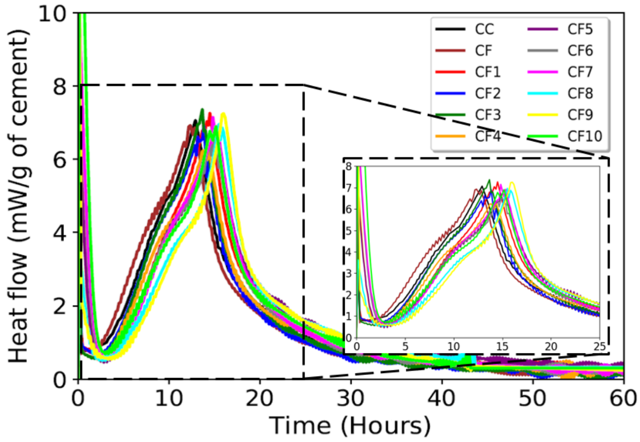

Figure 4. Heat flow–semiadiabatic calorimetry tests for different sediment-based concretes.

3.3. Compressive Strength

The compressive strength for a given concrete was obtained from compressive tests performed on three samples from the same batch loaded at the same time. The evolution of compressive strength between 3 days and 28 days is similar for all concretes (Figures 5 and 6). Therefore, the limited delay in hydration does not affect the compressive strength at 3 days. The substitution of cement by fine sediments induces a slight decrease in compressive strength, about 3 MPa (8%). The compressive strength of filler-based concrete is higher than that of fine sediment-based concrete but lower than that of control concrete. Dang et al. [13] showed that a cement based on calcined sediments (650 and 850 °C for 5 h) developed a compressive strength better than limestone filler but lower than that of the control mortar. In contrast to calcined fine sediments, the untreated sediments do not have significant pozzolanic effects and, therefore, the development of compressive strength for fine sediment-based concrete is limited. However, the use of calcined sediments as a substitute of cement substantially decreases the slump of the concrete [14,15,39]. The use of a plasticiser is therefore necessary to achieve the desired workability, which is not without affecting the compressive strength and delaying its setting [36].

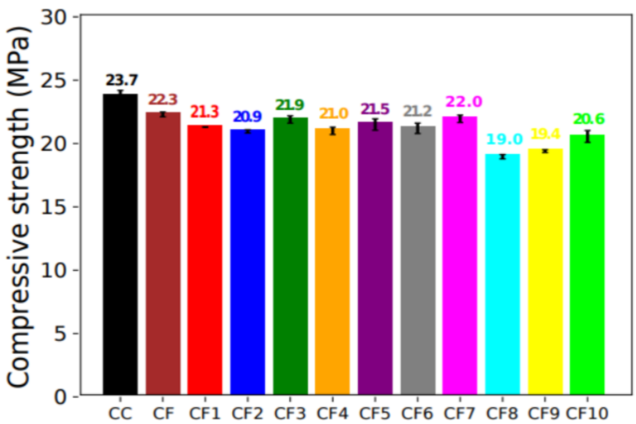

Figure 5. Compressive strength at 3 days.

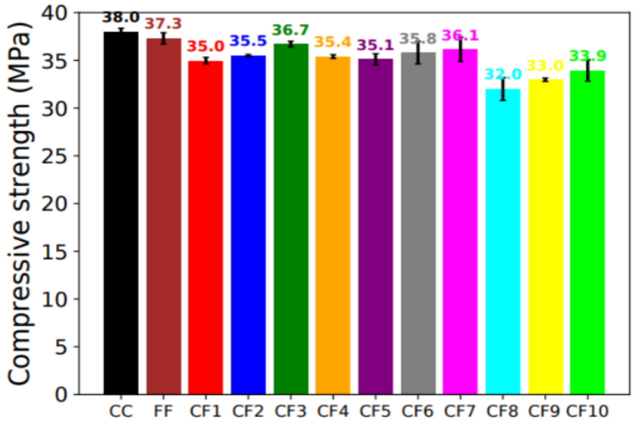

Figure 6. Compressive strength at 28 days.

3.4. Drying Shrinkage

The results of total shrinkage and weight loss are shown in Figures 7 and 8. Except for CF6 and CF7, the total shrinkage behaviour of filler-based concrete or fine sediment-based concrete is similar to that of control concrete. The used substitution method enables us to keep the same volume of paste in all concretes and therefore limit the variation of shrinkage from one concrete to another. However, the water demand, which can vary from one sediment to another, is likely to modify the water/cement ratio and thus the shrinkage behaviour of the cement paste. In addition, the mineralogical composition of the sediments can also affect the concrete shrinkage. For example, F6 and F7 may contain a significant fraction of clay, which increases their water demand. This results in an increase in swelling at an early age and in shrinkage afterward, due to drying [40]. The results of Zhao et al. [41] also show that greater shrinkage occurs in specimens with higher clay content, and this trend was more pronounced at latter ages.

Concerning the weight loss (Figure 8), the curves show no effect of the incorporation of sediments, even for those that show significant shrinkage. These results show that the F6 and F7 sediments respond differently to desiccation compared to the other sediments because they show greater shrinkage for a similar amount of water loss. The study of Zhao et al. [41] also showed that for similar mass loss, the pastes containing more clay show a higher drying shrinkage.

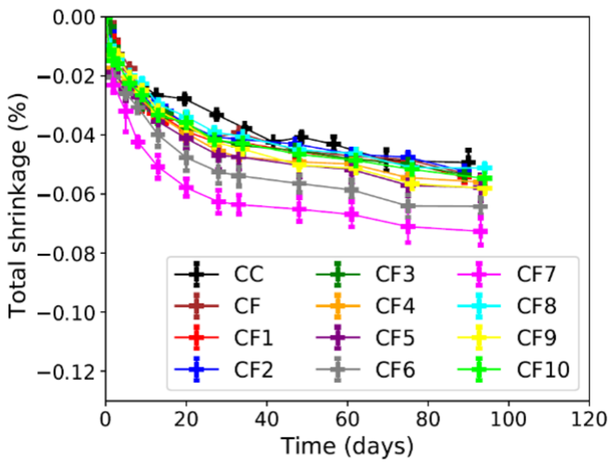

Figure 7. Total shrinkage vs. time.

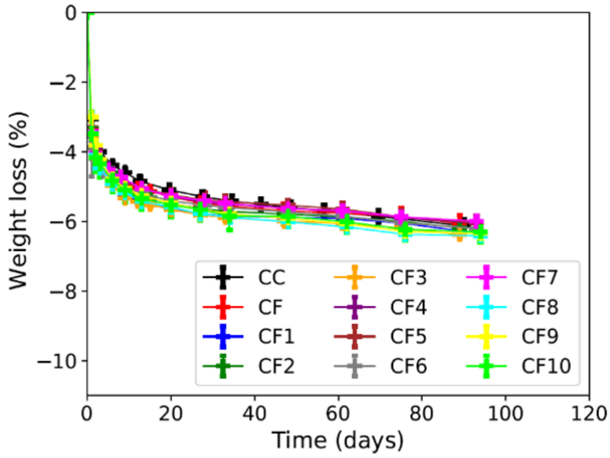

Figure 8. Weight loss vs. time.

4. Use of Fine Sediment: As Filler vs. as Sand

4.1. Technical Aspect

Table 5 summarizes the effect of incorporating sediments as an addition to cement or as sand on the various studied properties. The experimental results show that the use of fine sediments as a substitute for 10% of cement clearly has a more considerable technical benefit compared to their use as a substitute for 30% of sand. Admittedly, the second option reuses a larger volume of sediments, but the technical findings negate any possible environmental or economic benefits of this option and the volume of dredged sediments remains relatively modest and can be easily consumed by the huge concrete industry.

Table 5. Technical comparison of the use of fine sediments as filler or as sand (satisfying results are in green and unfavourable results are in red).

	Control Concrete	Fine Sediments as Sand (Substitution of 30%) [24]	Fine Sediments as Addition to Cement (Substitution of 10%)
Slump (cm)	18	16–18	18–21
Hydration delay (hours)	-	3–18	<4
Compressive strength (MPa)	38	18 (−53%) on average	35 (−8%) on average
Shrinkage at 90 days (%)	0.049	0.105 (+114%) on average	0.057 (+17%) on average
Valorised amount per m^3 of concrete	-	240 kg on average	29 kg on average

4.2. Environmental and Economic Aspects

In this paragraph, the environmental and economic benefits of the two incorporation options of fine sediments will be compared. Only the cost of the used ingredients and the carbon footprint of their production are considered in this paragraph. Table 6 shows the carbon footprint values of the production of the used ingredients in concrete mixtures. According to the sector guide carried out by ADEME in 2015, based on French data, the emission factors of cement type CEM I and natural aggregates are respectively 866 kg CO_2 eq/t and 2.3 kg CO_2/t. As the dredging operation is essential, the emission factors of the sediments are considered to be zero [42]. Figure 9 shows the carbon footprint of the production of 1 m^3 of concrete based on the values given in Table 6. The results show that the environmental benefit of incorporating fine sediments as sand is very low, while incorporating them as an addition to cement at only 10% reduces the carbon footprint of concrete by almost 10%. In fact, the carbon footprint of concrete is mainly due to that of cement production; thus, to reduce the concrete's carbon footprint, it is necessary to reduce its cement dosage. Table 6 also provides the unit prices of materials used in the laboratory.

The cost of sediments' pretreatment (drying, grinding, screening, etc.) was not considered in this study. The price of storing sediments in waste treatment facilities and the price at which treated sediments can be sold were also not taken into account. Figure 9 illustrates that the use of sediments as an addition to cement (or as sand) saves 6% (7%, respectively) of the concrete cost. Even if the cement price is more important, the large quantity of sand substituted by the sediments also provides a significant economic benefit of concrete based on sediments as sand.

In general, the incorporation of fine sediments into concrete, either as an addition to cement or as sand, provides environmental and economic benefits. Concerning the environmental aspect, the first mode of reuse largely outweighs the second. For the economic aspect, the use of fine sediments as sand does not show a significant advantage over their use as filler, which can compensate for the low concrete performance.

Table 6. Materials' carbon footprint and cost.

Ingredients	Concrete Mixtures (kg/m^3)			Carbon Footprint (kg CO_2 eq/t)	Cost (EUR/t)
	Control Concrete	Sediments as Sand	Sediments as Filler		
Cement	335	335	301.5	866	100
Aggregates	1695.5	1431.2	1695.5	2.3	15
Sediment	0	240.8	29.1	0	0

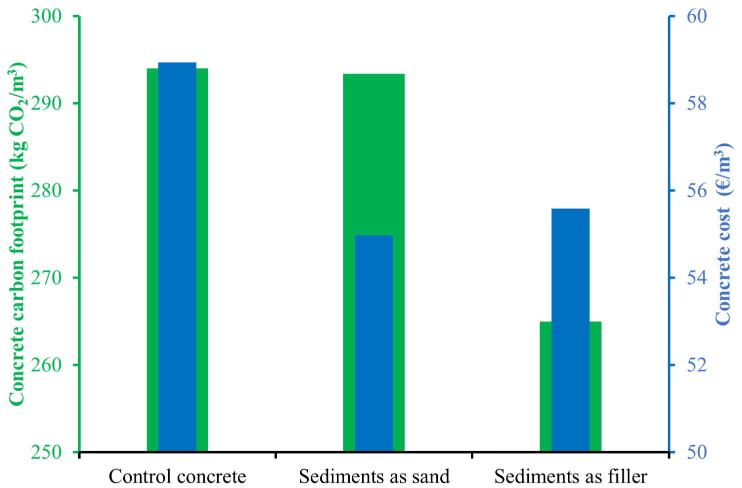

Figure 9. Carbon footprint and cost for different concretes (the green bars correspond to the carbon footprint and the blue bars correspond to the concrete cost).

5. Conclusions

The study aimed at investigating the effect of the incorporation of fine sediments from the Seine Basin deposit on the properties of concrete. Chemical analyses showed that these sediments are nonhazardous waste. Therefore, for environmental and economic benefits, these sediments were incorporated into the concrete without thermal treatment. The objective of this paper was first to evaluate the effect of substituting 10% of cement with fine sediments on the workability, the hydration, the compressive strength and the total shrinkage of C30/37 concrete. Then, the properties of concrete incorporating fine sediments as filler (10%) were compared to those of concrete incorporating fine sediments as sand (30%).

Keeping the same water/binder ratio, the substitution of 10% cement by fine sediments does not affect the workability of concrete. However, a slight delay in hydration, less than 4 h, has been observed for sediment-based concrete, which is attributed to the organic matter content of the untreated fine sediments. The compressive strength showed a slight decrease with the incorporation of fine sediments. This decrease remains limited to 8% on average. As for total shrinkage, with the exception of two sediments, the behaviour of the fine sediment-based concrete is similar to that of the control concrete. The presence of mineral components such as clay in these two sediments could be at the origin of these observations. Indeed, as sediments are heterogeneous materials, the observed effects on concrete properties can be attributed to the presence of a given component, such as humic substances or clay, or to a combined effect of several components.

Regarding the comparison between the use of sediments as an addition to cement or as sand in concrete, the results show that the latter has only one advantage, as it allows for the reuse of a greater volume. On the other hand, the incorporation of sediments as an addition to cement offers acceptable technical performance as well as a reduction in the environmental and economic costs of concrete because it aims to substitute cement, which is the most expensive ingredient from an environmental and economic point of view. Moreover, the use of 10% of fine sediments as cement is enough to consume the entire sediment deposit, which is still relatively small compared to the large quantity of concrete produced in the region.

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References

1. Iqbal, M.F.; Liu, Q.; Azim, I.; Zhu, X.; Yang, J.; Javed, M.F.; Rauf, M. Prediction of mechanical properties of green concrete incorporating waste foundry sand based on gene expression programming. *J. Hazard. Mater.* **2020**, *384*, 121322. [CrossRef] [PubMed]
2. Iqbal, M.F.; Javed, M.F.; Rauf, M.; Azim, I.; Ashraf, M.; Yang, J.; Liu, Q. Sustainable utilization of foundry waste: Forecasting mechanical properties of foundry sand based concrete using multi-expression programming. *Sci. Total Environ.* **2021**, *780*, 146524. [CrossRef] [PubMed]
3. Ashraf, M.; Iqbal, M.F.; Rauf, M.; Ashraf, M.U.; Ulhaq, A.; Muhammad, H.; Liu, Q. Developing a sustainable concrete incorporating bentonite clay and silica fume: Mechanical and durability performance. *J. Clean. Prod.* **2022**, *337*, 130315. [CrossRef]
4. Tazi, N.; Idir, R.; Ben Fraj, A. Towards achieving circularity in residential building materials: Potential stock, locks and opportunities. *J. Clean. Prod.* **2021**, *281*, 124489. [CrossRef]
5. Idir, R.; Ben Fraj, A. Concrete based on recycled aggregates—Recycling and environmental analysis: A case study of paris' region. *Constr. Build. Mater.* **2017**, *157*, 952–964.
6. Idir, R.; Cyr, M.; Pavoine, A. Investigations on the durability of alkali-activated recycled glass. *Constr. Build. Mater.* **2020**, *236*, 117477. [CrossRef]
7. DTBS. *Bilan des Opérations de Dragage du Bassin de la Seine en 2018*; Direction Territoriale Bassin de la Seine: Paris, France, 2019. (In French)
8. ADEME. *Etude sur le Prix D'élimination des Déchets Inertes du BTP*; Direction Consommation Durable et Déchets–ADEME: Paris, France, 2012. (In French)

9. Kasmi, A.; Abriak, N.-E.; Benzerzour, M.; Azrar, H. Environmental impact and mechanical behavior study of experimental road made with river sediments: Recycling of river sediments in road construction. *J. Mater. Cycles Waste Manag.* **2017**, *19*, 1405–1414. [CrossRef]
10. Kamali, S.; Bernard, F.; Abriak, N.; Degrugilliers, P. Marine dredged sediments as new materials resource for road construction. *Waste Manag.* **2008**, *28*, 919–928.
11. Bellara, S.; Hidjeb, M.; Maherzi, W.; Mezazigh, S.; Senouci, A. Optimization of an Eco-Friendly Hydraulic Road Binders Comprising Clayey Dam Sediments and Ground Granulated Blast-Furnace Slag. *Buildings* **2021**, *11*, 443. [CrossRef]
12. Van Bunderen, C.; Snellings, R.; Vandewalle, L.; Cizer, O. Early-age hydration and autogenous deformation of cement paste containing flash calcined dredging sediments. *Constr. Build. Mater.* **2019**, *200*, 104–115. [CrossRef]
13. Dang, T.A.; Kamali-Bernard, S.; Prince, W.A. Design of new blended cement based on marine dredged sediment. *Constr. Build. Mater.* **2013**, *41*, 602–611. [CrossRef]
14. Ez-zaki, H.; Diouri, A. Microstructural and physico-mechanical properties of mortars-based dredged sediment. *Asian J. Civ. Eng.* **2019**, *20*, 9–19. [CrossRef]
15. Benzerzour, M.; Amar, M.; Abriak, N.-E. New experimental approach of the reuse of dredged sediments in a cement matrix by physical and heat treatment. *Constr. Build. Mater.* **2017**, *140*, 432–444. [CrossRef]
16. Safhi, A.-E.; Rivard, P.; Yahia, A.; Benzerzour, M.; Khayat, K.H. Valorization of dredged sediments in self-consolidating concrete: Fresh, hardened, and microstructural properties. *J. Clean. Prod.* **2020**, *263*, 121472. [CrossRef]
17. Hadj Sadok, R.; Belas, N.; Tahlaiti, M.; Mazouzi, R. Reusing calcined sediments from Chorfa II dam as partial replacement of cement for sustainable mortar production. *J. Build. Eng.* **2021**, *40*, 102273. [CrossRef]
18. Benzerzour, M.; Maherzi, W.; Amar, M.; Abriak, N.-E.; Damidot, D. Formulation of mortars based on thermally treated sediments. *J. Mater. Cycles Waste Manag.* **2018**, *20*, 592–603. [CrossRef]
19. Zhao, Z.; Benzerzour, M.; Abriak, N.-E.; Damidot, D.; Courard, L.; Wang, D. Use of uncontaminated marine sediments in mortar and concrete by partial substitution of cement. *Cem. Concr. Compos.* **2018**, *93*, 155–162. [CrossRef]
20. Agostini, F.; Skoczylas, F.; Lafhaj, Z. About a possible valorisation in cementitious materials of polluted sediments after treatment. *Cem. Concr. Compos.* **2007**, *29*, 270–278. [CrossRef]
21. Limeira, J.; Etxeberria, M.; Agulló, L.; Molina, D. Mechanical and durability properties of concrete made with dredged marine sand. *Constr. Build. Mater.* **2011**, *25*, 4165–4174. [CrossRef]
22. Said, I.; Missaoui, A.; Lafhaj, Z. Reuse of Tunisian marine sediments in paving blocks: Factory scale experiment. *J. Clean. Prod.* **2015**, *102*, 66–77. [CrossRef]
23. Beddaa, H.; Ben Fraj, A.; Ducléroir, S. Experimental study on river sediment incorporation in concrete as a full aggregate replacement: Technical feasibility and economic viability. *Constr. Build. Mater.* **2021**, *313*, 125425. [CrossRef]
24. Beddaa, H.; Ouazi, I.; Ben Fraj, A.; Lavergne, F.; Torrenti, J.-M. Reuse potential of dredged river sediments in concrete: Effect of sediment variability. *J. Clean. Prod.* **2020**, *265*, 121665. [CrossRef]
25. Millrath, K.; Kozlova, S.; Shimanovich, S.; Meyer, C. *Beneficial Use of Dredge Material. Progress Report Prepared for Echo Environmental*; Columbia University: New York, NY, USA, 2001.
26. Ouédraogo, N.P.; Becquart, F.; Benzerzour, M.; Abriak, N.-E. Influence of fine sediments on rheology properties of self-compacting concretes. *Powder Technol.* **2021**, *392*, 544–557. [CrossRef]
27. Legifrance. *Arrêté du 12 Décembre 2014, Relatif Aux Conditions D'admission des Déchets Inertes Dans les Installations Relevant des Rubriques 2515, 2516, 2517 et dans les Installations de Stockage de Déchets Inertes Relevant de la Rubrique 2760 de la Nomenclature des Installations Classées*; Legifrance: Paris, France, 2014. Available online: https://www.legifrance.gouv.fr/loda/id/JORFTEXT000029893828/ (accessed on 20 November 2021). (In French)
28. Legifrance. *Arrêté du 9 Août 2006, Relatif aux Niveaux à Prendre en Compte lors D'une Analyse de Rejets dans les Eaux de Surface ou de Sédiments Marins, Estuariens ou Extraits de Cours d'eau ou Canaux Relevant Respectivement des Rubriques 2.2.3.0, 4.1.3.0 et 3.2.1.0 de la Nomenclature Annexée à L'article r. 214–1 du code de L'environnement*; Legifrance: Paris, France, 2006. Available online: https://www.legifrance.gouv.fr/loda/id/JORFTEXT000000423497/ (accessed on 20 November 2021). (In French)
29. *EN12350-2*; Testing Fresh Concrete–Part 2: Slump Test. Françaisede Normalization: Paris, France, 2012.
30. *EN196-9*; Methods of Testing Cement—Part 9: Heat of Hydration-Semi-Adiabatic Method. Françaisede Normalization: Paris, France, 2010.
31. *EN12390-3*; Testing Hardened Concrete—Part 3: Compressive Strength of Test Specimens. Françaisede Normalization: Paris, France, 2012.
32. *NF P 15-433*; Cement Test Methods—Determination of Shrinkage and Swelling. Françaisede Normalization: Paris, France, 1994.
33. Beddaa, H.; Ben Fraj, A.; Lavergne, F.; Torrenti, J.-M. Effect of potassium humate as humic substances from river sediments on the rheology, the hydration and the strength development of a cement paste. *Cem. Concr. Compos.* **2019**, *104*, 103400. [CrossRef]
34. Agostini, F.; Davy C.A.; Skoczylas, F.; Dubois, T. Effect of microstructure and curing conditions upon the performance of a mortar added with Treated Sediment Aggregates (TSA). *Cem. Concr. Res.* **2010**, *40*, 1609–1619. [CrossRef]
35. Van Bunderen, C.; Benboudjema, F.; Snellings, R.; Vandewalle, L.; Cizer, Ö. Experimental analysis and modelling of mechanical properties and shrinkage of concrete recycling flash calcined dredging sediments. *Cem. Concr. Compos.* **2021**, *115*, 103787. [CrossRef]

36. Chen, H.; Wang, Q. The behaviour of organic matter in the process of soft soil stabilization using cement. *Bull. Eng. Geol. Environ.* **2006**, *65*, 445–448. [CrossRef]
37. Beddaa, H.; Ben Fraj, A.; Lavergne, F.; Torrenti, J.-M. Early-Age Shrinkage of Cement Paste Containing Humic Substances as that from River Dredging Sediments in France. *Symp. Paper* **2021**, *349*, 23–39.
38. *EN 1744-1:2009+A1:2012*; Tests for Determining the Chemical Properties of Aggregates—Part 1: Chemical Analysis. Afnor: Paris, France, 2014.
39. Snellings, R.; Horckmans, L.; Van Bunderen, C.; Vandewalle, L.; Cizer, O. Flash-calcined dredging sediment blended cements: Effect on cement hydration and properties. *Mater. Struct.* **2017**, *50*, 1–12. [CrossRef]
40. Buth, E.; Ivey, D.L.; Hirsch, T.J. *Clay, Aggregate, and Concrete*; Deleterious Materials in Concrete; Texas A&M University: College Station, TX, USA, 1967; p. 34
41. Zhao, H.; Ma, Y.; Zhang, J.; Hu, Z.; Li, H.; Wang, Y.; Liu, J.; Wang, K. Effect of clay content on shrinkage of cementitious materials. *Constr. Build. Mater.* **2022**, *322*, 125959. [CrossRef]
42. ADEME. *Guide Sectorial 2015: Réaliser une Analyse Environnementale Dans les Travaux Publics*; ADEME: Paris, France, 2015. (In French)