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Mineral Processing Techniques Dedicated to the Recycling of River Sediments to Produce Raw Materials for Construction Sector

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Abstract: Dredged river sediments produce a huge volume of mineral materials, which could be incorporated into building materials. Considering the raw sediment preparation, mineral processing techniques fit perfectly to this purpose. This work describes two procedures to prepare river sediments, according to the final beneficial use. The first is a dry procedure of deagglomeration to prepare river sediments with the aim of being incorporated into a concrete formulation to build a bicycle path. A large amount of deagglomerated sediment was prepared, requiring upscaling of the deagglomeration process. Successive steps of sieving and roll crushing were used to obtain deagglomerated sediments. To use it as raw material to produce pozzolanic materials and lightweight aggregates, a second procedure consisting of a wet classification at 63 µm was carried out. Steps of wet sieving, followed by hydrocycloning and screw classifying, were used to prepare several silt fractions under 63 µm.

Keywords: dredged sediment; mineral processing; crushing; classification; concrete

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1. Introduction

The accumulation of sediments in waterways is a serious and recurrent problem for navigation. For maintaining shipping and hydraulic flow, regular dredging of these channels is necessary, generating a huge amount of materials and a significant part of which is polluted. According to the SedNet network [1], 200 million of m^3 are dredged each year in Europe. In Belgium, 990 km of channels are found in the Flanders region while 450 km are managed by the Walloon region. For the sole Walloon region, the annual amount of dredged material varies between 100,000 and 250,000 m^3/year from 2010 to 2020 [2]. Moreover about 3,000,000 m^3 of sediment to be dredged remain in the channels, according to the Walloon waterway managing authority, because of the lack of technical and economical solutions. In the North of France, annual dredging represents around 100,000 m^3 of river sediments for 680 km of waterways, according to the French waterway managing authority. In the European Union, dredged sediment is considered as waste under EU Directives [3] and is usually landfilled. However, river sediments are mainly constituted of valuable minerals and could be a source of raw materials for construction if adequate pre-treatments were applied. Mineral processing techniques fit perfectly with this goal, as they do not require sophisticated equipment and, therefore, are cheap. This approach would contribute to the circular economy objectives [4] by reducing as far as possible the volume of sediments to be landfilled and by reducing the demand for primary minerals.

Dredged sediments can be incorporated in many construction materials: into concrete or mortars as replacement of sand [5–12] or cement [13–15], filling material for embankments [16], as road sub-layer [17–19], and into ceramic phases such as bricks [20–22] or lightweight aggregates [23–26]. Nevertheless, several challenges must be overcome to use river sediment as raw materials for the building sector, including social, legislative, economic as well as technical or scientific challenges. The social acceptance of using building materials from secondary and polluted sources is often low [22]. Legislations enforce more and more stringent pollutant's maximum levels and are not always consistent between countries and regions of the European Union. Some beneficial uses are also not allowed by local legislation. The economic aspect is important too: besides the dredging and transport costs, treatment costs have to be added [27]:

- Calcination: generally expensive (higher than 90 €/ton dry matter [DM]);
- Stabilisation/solidification: use of reactants, generally expensive (50–75 €/ton DM);
- Size classification: comprises a lot of steps (±30 €/ton DM);
- Flotation: use of expensive reactants (10–40 €/ton DM).

The most important challenges remain scientific. Dredged sediments are known to be heterogeneous (exogenous materials can be found in the sediment, and with a large particle size distribution), high water-containing materials and often polluted (sometimes highly) [13]. The main problems are the risk of leaching-out of the pollutants and the presence of organic matter, which influences the mechanical properties of the building material made with sediments or influences the properties of the bricks [21]. Nevertheless, the use of mineral processing techniques allows to overcome several challenges:

- The presence of unwanted size fractions can be treated by applying sieving or hydrocyclone techniques. Hydrocycloning was evaluated by Kim et al. [28,29] to remediate dredged sediments contaminated with heavy metals. These pollutants are concentrated in the fine fraction [30].
- The presence of organic matter (and organic pollutants) can be reduced by thermal treatment [31,32] or by attrition followed by gravimetric separation [33].
- Heavy metals can be stabilised using specific reactants, such as in the Novosol® process (treatment with phosphoric acid to synthesize apatite which retains some heavy metals followed by thermal treatment to reduce organic pollutant levels; [34]) or can be partially removed by froth flotation [35,36].
- Some crystalline phases can have unwanted effects, for example clayey swelling phases, but it can be removed by size classification or froth flotation techniques.

Some industrial plants are known to use mineral processing techniques on sediments. The Hamburg port authority (METHA plant; [37,38]) and the Port of Antwerp (AMORAS plant; [39,40]) are currently using mineral processing to treat dredged harbour sediments. The main techniques applied in those plants are size classifications using screens and hydrocyclones to recover sandy fractions, followed sometimes by gravimetric separation.

This paper presents the techniques used to treat three different river sediments from Belgium and France, aiming to incorporate it in:

- Concrete used to build a bicycle path: a dry deagglomeration process has been set up and upscaled to supply a large amount of material (13.5 tons). In fact, lagooned sediments can contain large agglomerate blocks (some larger than 0.5 m), which cannot be accommodated inside a concrete mixer. An additional challenge is to deagglomerate the sediment without reducing excessively its moisture content.
- Pozzolanic materials and lightweight clay aggregates, using a wet size classification platform, allowing the separation of the dredged sediments at 63 μm.

This work was carried out under the VALSE project [41], which includes the demonstration of the beneficial uses of dredged sediments by building large demonstrators, especially a large bicycle path in concrete which contains sediment.

2. Materials and Methods

Mineral processing techniques are generally simple, cheap and do not rely on the extensive use of chemical reactants. They can be classified between dry or wet techniques. Both were used in this project, to reach different goals:

- Dry techniques were used to treat dehydrated river sediments with the aim to deagglomerate them and to incorporate them into a concrete formula, with the final goal being the building of a bicycle path. This concrete is formulated by a project partner and will be the subject of a further publication.
- Wet techniques were used to separate the −63 µm fraction. The final goal was to produce pozzolanic materials [15] or to incorporate the fraction into lightweight clay aggregates [26]; both beneficial uses are thermal techniques. In fact, pozzolanic materials are produced by calcining clay materials at 700–800 °C. Lightweight clay aggregates are formed at temperatures between 1000 and 1100 °C.

2.1. River Sediments and Characterisation

Three river sediments batches were used in this work. The first Walloon sediment was dredged from the Charleroi-Bruxelles channel (location called "Bief 1"), then sieved at 5 mm and finally dehydrated in the Sedisol lagoon (Farciennes, Belgium). This sediment is hereunder abbreviated as SLS (Sedisol Lagoon Sediment).

The second Walloon sediment was recovered from the lagoon of Ampsin (province of Liège, Belgium). This sediment comes from different channel locations and was not previously sieved. This sediment is hereunder abbreviated as ALS (Ampsin Lagoon Sediment).

The third sediment comes from a French river and was also previously dehydrated in the Noyelles-sous-Lens lagoon, without previous sieving. This sediment is hereunder abbreviated as NLS (Noyelles Lagoon Sediment).

To define the relevant pre-treatment operations aiming the beneficial use of river sediments, a full physicochemical characterisation of these materials must be carried out.

Sediment particle size distribution was determined by combining several techniques including wet sieving steps up to 38 µm, hydrocycloning of the undersize at 25 µm and laser particle size analysis on the (−38; +25 µm) and (−25 µm) fractions using a Cilas 1180 L Laser particle size analyser.

The chemical composition (major elements and heavy metals) of the sediments was analysed by digestion and Inductively Coupled Plasma measurement. A sediment sample was digested with aqua regia under reflux for 4 h. After filtration, the residue underwent alkaline fusion in a crucible in the presence of fluxes [NaOH and Na_2O_2]. The solution resulting from the alkaline fusion and the filtrate of the aqua regia digestion was then analysed by Inductively Coupled Plasma (ICP-OES), using a Perkin Elmer Optima 7300 DV.

Mercury was analysed using a Leco Ama 254 apparatus and fluoride was analysed by titrimetry using a Dionex ICS2000. Cyanide content was analysed by UV-visible spectrometry.

Crystalline phases were analysed by an X-ray diffraction technique with a random distribution powder. Measurements were carried out with a Bruker D8 Advance Davanci diffractometer in Bragg-Brentano configuration, equipped with an X-ray tube with Cu anode ($K_{\alpha1,2}$) and one rapid linear sensor with high resolution (LYNXEYE).

Leaching tests were carried out by following the EN 12457-2 standard, as required by legislation [42]. A mixture of sediment and ultrapure water (with a liquid/solid ratio of 10) was mixed using a bottle roll during 24 h, to allow exchangeable pollutants to pass through the liquid phase. Pollutant levels in the leachate were recorded by ICP-OES and converted into $mg/kg_{dry\ matter}$, according to reference [42].

2.2. Dry Techniques Used to Deagglomerate a River Sediment

In the concrete mixing plant, the sediments are introduced into the concrete mixer as solid material; therefore, dry mineral processing techniques were privileged. Challenges for deagglomeration will be detailed in Section 3.2, but include size reduction of sediment agglomerates under 20 mm (to allow a good dispersion and better feed into the concrete mixer) without reducing excessively the sediment moisture content.

Preliminary trials were carried out with different techniques, such as screw feeder, shredding or roll crusher technologies. The two last ones are size reduction technologies.

The screw feeder is composed of two parallel screws (Figure 1) which allow a continuous mixing of the products. The paddles ensure an alternative effect of penetration and chopping during the progression in the products. The effect of shear induced by the two parallel screws can be used to deagglomerate large blocks of sediment. The screw feeder MPS120 from SOFRADEN, which demonstrates a maximum flow rate of 0.5 m^3/h, was used in this study.

Figure 1. Inside view of the screw feeder SOFRADEN MPS120.

The shredders consist of independent rotors with a series of knives that cross between the rotors (Figure 2). These knives are adjusted to avoid friction between them. The knives ensure that the material to be shredded is picked up and introduced between the flanks of the discs. The equipment used in this study is the DECOVAL 3K7/30, with a maximum flow rate of 400 kg per hour.

Figure 2. Inside view of the shredder DECOVAL 3K7/30.

Three different roll crusher configurations were tested: single roll shredder, toothed roll crusher and fluted roll crusher. Single roll shredder is composed of one crushing cylinder equipped with several teeth (Figure 3). A push-piece forces the contact between the material and the cylinder. The used equipment is a “monorotor” grinder model MPG 15 (Wagner WS 15) of 18.7 kW from the Wagner Company, with a maximum flow rate of 500 kg per hour.

Figure 3. Inside view of the single roll shredder (**top**: toothed cylinder, **bottom**: push-piece).

The toothed roll crusher is equipped with two opposite toothed cylinders (Figure 4). Compared to other roll crushers, the toothed roll crusher allows treating moderately wet materials and the resulting crushed fraction is coarser (less than 15 mm). The used equipment is a home-made pilot crusher (model ALC 300/400) of 13 kW, which can work until 3 tons per hour.

Figure 4. Inside view of the toothed roll crusher.

The fluted roll crusher is equipped with two opposite cylinders displaying waves on their external surface (Figure 5). Treated materials must be sufficiently dry and the resulting crushed fraction can be fine (few millimetres). The used equipment is a home-made pilot crusher (model ALC 400/500) of 8 kW, which can work until 4 tons per hour.

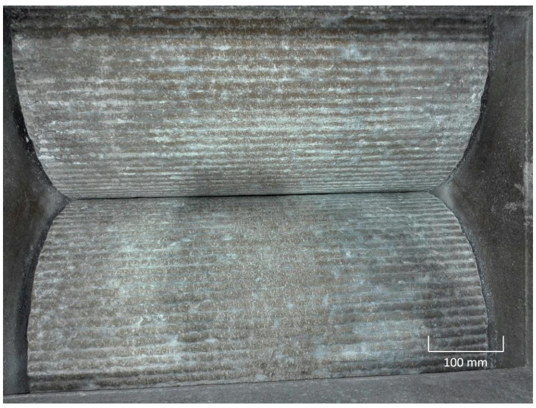

Figure 5. Inside view of the fluted roll crusher.

Sieving by vibrating screens was used to assess the size reduction of agglomerates obtained by crushing. Screens with 5 or 10 mm apertures were mounted on a double deck screening machine (SZLN 500–1500 from SPALECK). A large rotating drum sieve (trommel) was also used for production of large batches.

To help the deagglomeration process, the river sediments were dried in ambient air inside a covered area.

2.3. Wet Techniques Used to Isolate a −63 µm Fraction

The −63 µm fraction is prepared by wet mineral processing techniques, available on the semi-automated SOLINDUS pilot platform [43–45], described in Figure 6. This platform includes several steps of size classification and physicochemical treatment (froth flotation, attrition, etc.) and contains all peripheral devices necessary for continuous operations (pumps, tanks, decanters, etc.). Among all the equipment, the following were used to recover the −63 µm fraction:

- Wet sieving at 2 mm, using a rotating trommel (working up to 1.2 t/h dry matter on a slurry with a dry matter content of 40–80%) and a vibrating screen (working till 1.2 t/h dry matter on a slurry with a dry matter content of 30–40%);
- Wet sieving at 250 µm on a curved screen (working till 1.2 m^3/h on a slurry with a dry matter content of 10–20%);
- A classification at 63 µm using two devices in series: a hydrocyclone (working till 1.2 m^3/h on a slurry with a dry matter content of 10–40%) and a screw classifier (working up to 0.8 m^3/h on a slurry with a dry matter content of 10–40%). The underflow fraction of the hydrocyclone is refined by the screw classifier. The coarse fraction (+63 µm) is recovered at the discharge of the screw and the overflow fraction of the screw classifier goes back to the hydrocyclone.

The −63 µm fraction reports to the overflow fraction going out the hydrocyclone. This fraction is finally dehydrated with a WITH US SKFP 500 filter-press, allowing to recover a solid fraction. This equipment disposes of 9 plates allowing demonstrating 10 filtration chambers with a dimension of 40 × 40 cm.

The SOLINDUS pilot platform has a capacity up to 1 ton/h (on dry matter basis), and is semi-automatised and flexible: each equipment can work independently, and the platform is able to treat various kinds of mineral materials (dredging sediments, excavated soils, etc.). Other treatments than previously described are also available in the pilot platform (Figure 6), such as a smaller hydrocyclone (cut off at 15 µm), froth flotation, washing by attrition and gravimetric separation by spirals.

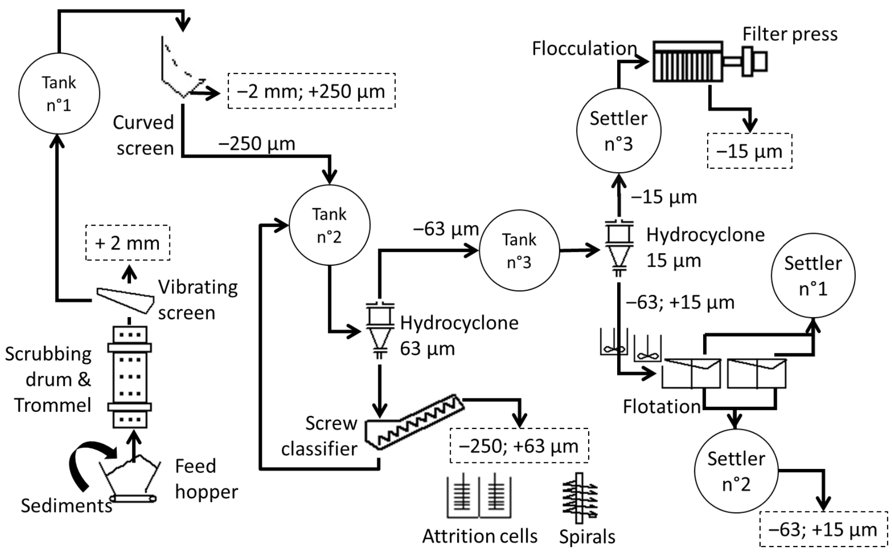

Figure 6. General scheme of the SOLINDUS pilot platform.

A wide range of techniques is therefore available to adjust the physicochemical properties of sediments.

3. Results

3.1. Sediment Characterisation

3.1.1. Particle Size Distribution

The particle size analysis reveals that the SLS sediment is very fine with more than 70% below 63 µm (see Figure 7). The finest fraction (−25 µm) represents approximately 60% of the material. An amount of 17% of the material is made of sand (−1.7 mm; +63 µm). The ALS sediment still demonstrates a finer particle size with 78.8% of the sediment below 63 µm, with less than 60% below 25 µm. On the other hand, the NLS sediment has a high proportion of coarse elements (exogenous, aggregates . . .), because it was not screened before it entered the lagoon. Nevertheless, if this exogenous fraction is removed, the relative proportions of (−25 µm) and (−63; +25 µm) are equivalent to the values found for the SLS and ALS sediments.

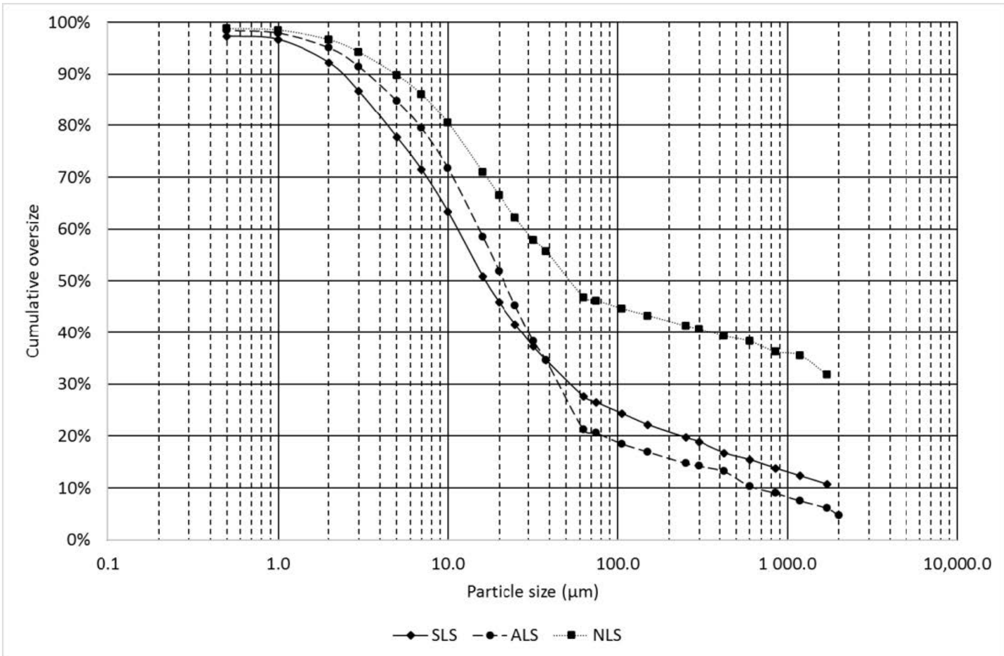

Figure 7. Particle size distribution of each sediment sample.

3.1.2. Chemical Composition

As observed in Table 1, analysis of major elements in the three sediments demonstrates the silicate nature of the sediment. Other major elements are Fe, Al, Ca and K. Qualitative XRD analysis reveals major crystalline phases: quartz, calcite, some feldspaths (albite, microcline), muscovite and other phyllic phases (clinochlore, kaolinite).

Table 1. Major element levels (%) in each sediment.

Sediments	Si	Fe	Al	Ca	K	SO_4	P	Mg	Na	Zn
SLS	20.92	6.68	6.15	2.69	1.70	1.30	0.42	0.62	0.42	0.30
ALS	22.14	3.14	4.39	7.22	1.30	0.58	0.24	0.90	0.40	0.10
NLS	17.67	3.09	4.83	8.63	1.31	2.18	0.62	0.55	0.40	0.21

In the Walloon region, sediments are classified as "A" or "B" according to the Walloon Government Agreement of 30 November 1995 [42]. Sediments with all pollutant levels below the threshold called "maximum allowable content" (see Table 2 for values) are classified as "A", namely less polluted sediments. Sediments with at least one pollutant level above the threshold called "safety level" are classified as "B". Sediments with all pollutant levels below the safety level, but at least one between the maximum allowable content and the safety level, must undergo a leaching test to be classified. If all pollutant leaching concentrations are below the maximum allowable concentration, the sediment can be classified as "A"; if at least one pollutant leaching concentration is above the corresponding maximum allowable concentration, the sediment is classified as "B".

Table 2. Comparison between Walloon and French legislations about inorganic pollutant levels ($mg/kg_{dry\ matter}$) allowed in dredging sediment.

Inorganic Pollutants	Wallonia *			France **	
	Maximum Allowable Content	**Safety Level**	**Maximum Allowable Content in Leachate**	**N1**	**N2**
As	50	100	0.5	25	50
Cd	6	30	0.1	1.2	2.4
Co	25	100	0.5	-	-
Cr	200	460	0.5	90	180
Cu	150	420	2	45	90
Hg	1.5	15	0.02	0.4	0.8
Ni	75	300	0.5	37	74
Pb	250	1500	0.5	100	200
Zn	1200	2400	2	276	552
F^-	250	500	20	-	-
CN^-	5	25	0.1	-	-

* according to Walloon government agreement of 30 November 1995 [42]. ** according to GEODE [46].

Unlike the Walloon legislation, the French regulation on dredged river sediments is based on risk analysis. Nevertheless, two pollutant thresholds are defined, called N1 and N2 (see Table 2). These were intended for sea immersion but are usually applied to inland sediments for comparison purposes. Below the N1 level, the dumping at sea of dredged material would be authorised without any further studies. Above the N2 level, the dumping is likely to be prohibited as long as inland disposal is the least harmful option for the environment. Between N1 and N2 levels, further studies (risk analysis) are required. Nevertheless, to gather certain references about limit values, pollutant levels of the French sediment were compared with the Walloon legislation limits.

As observed in Table 3, SLS sediment is heavily polluted with Cd, Zn and cyanide (values above the corresponding safety levels). It is moderately contaminated with Cu, Pb and F^- (values between the admissible values and the safety levels). Since the contents of Cd, Zn and CN^- exceed the safety content, this sediment is classified as "B", namely polluted, without the need of any additional leaching test. Compared to the raw SLS sediment, the fine fraction (−25 µm) concentrates inorganic pollution, especially in Cd, Zn and cyanides. The values are such that the fine fraction would be classified as "B" (polluted) according to the regulation. The other fractions have contents either below the admissible value defined by the regulation (As, Co, Cr, Cu, and Hg) or values between the admissible value and the safety level (Cd, Ni, Pb, Zn, F^- and CN^-). The sandy and silty (−63; +25 µm) fractions could undergo a leaching test to classify these fractions, but this test was not performed, because the source material was already classified as "B".

Table 3. Mass content distribution and inorganic pollutant level distribution inside SLS sediment compared to the thresholds specified in [42].

		Size Fractions						Maximum Allowable Content *	Safety Level *
		Raw	**(+1.7 mm)**	**(−1.7 mm; +250 µm)**	**(−250; +63 µm)**	**(−63; +25 µm)**	**(−25 µm)**		
Mass distribution (%)		-	10.7	9.0	7.9	14.0	58.4	-	-
Pollutant levels ($mg/kg_{dry\ matter}$)	As	28.4	10.8	31.1	18.3	26.1	*61.8*	50	100
	Cd	**55.7**	<10	*24.1*	*13.7*	*26.4*	**150.8**	6	30
	Co	<25	<10	<10	<10	<10	<10	25	100
	Cr	176.8	121.0	144.4	103.1	154.5	*295.7*	200	460
	Cu	*190.6*	41.3	107.3	86.0	118.5	*305.2*	150	420
	Hg	0.8	0.12	0.42	0.37	1.04	*1.55*	1.5	15
	Ni	73.0	53.6	62.3	62.2	*87.0*	*165.0*	75	300
	Pb	*531.5*	44.0	230.3	221.3	*293.1*	*938.3*	250	1500
	Zn	**3023.0**	388.8	*1288.0*	822.0	*1350.6*	**5615.1**	1200	2400
	F^-	*439.2*	*313.3*	*498.8*	*300.3*	*283.0*	*473.9*	250	500
	CN^-	**60.1**	3.9	*20.0*	*6.7*	*22.0*	**130.0**	5	25

* according to Walloon government agreement of 30 November 1995 [42]. Bold characters: contents above the safety level. Italic characters: contents between the maximum allowable content and the safety limit.

The ALS sediment is less polluted than the SLS sediment, as observed in Table 4. Only fluoride level exceeds the safety limit in the raw material. This is due to the high concentration of fluoride in the coarse fraction (+2 mm). Cadmium content is between the maximum allowable content and the safety limit, and this is observed for all size fractions, except the coarser fraction. Compared to raw sediment, ALS fine fraction (−25 µm) concentrates most of the pollutants (Cd, Cr, Pb, Zn), except fluoride. Fluoride balance does not fit between analysis of the whole sample and reconstitution based on particle size fractions. Fluorides leaching due to wet sieving, as well as sediment sampling problems, could be a cause of this discrepancy.

Table 4. Mass content distribution and inorganic pollutant level distribution inside ALS sediment compared to the thresholds specified in [42].

		Size Fractions						Maximum Allowable Content *	Safety Level *
		Raw	**(+2 mm)**	**(−2 mm; +250 µm)**	**(−250; +63 µm)**	**(−63; +25 µm)**	**(−25 µm)**		
Mass distribution (%)		-	4.7	10.1	6.5	24.0	54.8	-	-
Pollutant levels ($mg/kg_{dry\ matter}$)	As	<10	<5	6.9	11.1	8.4	18.8	50	100
	Cd	*25.3*	5.2	*13.6*	*33.5*	*18.4*	30.1	6	30
	Co	11.5	<5	7.6	19.0	11.4	18.2	25	100
	Cr	164.9	44.3	83.2	116.0	157.7	*236.8*	200	460
	Cu	89.0	16.0	46.3	122.6	84.6	*156.5*	150	420
	Hg	0.9	0.0	0.2	1.1	0.5	1.1	1.5	15
	Ni	41.6	24.4	38.4	63.9	46.1	58.2	75	300
	Pb	197.0	17.0	59.5	144.3	110.4	*365.8*	250	1500
	Zn	967.0	120.2	451.2	958.6	636.4	*1419.8*	1200	2400
	F^-	**569.2**	**867.0**	233.0	218.8	231.6	205.7	250	500
	CN^-	2.0	<1.0	<1.0	<1.0	<1.0	4.3	5	25

* according to Walloon government agreement of 30 November 1995 [42]. Bold characters: contents above safety limit. Italic characters: contents between maximum allowable content and safety limit.

The raw NLS sediment differs significantly from the SLS and ALS sediments in terms of pollution (Table 5). The NLS sediment is heavily polluted with Cu (above the safety level). It is also moderately polluted with Hg, Pb, Zn, fluoride, and cyanides (value between the permissible value and the safety content). This sediment can therefore be considered as polluted under [42]. The Table 5 also displays a concentration of the pollution into the fines

(−25 µm), mainly in As, Cu, Pb, Zn and cyanide. However, the observed concentration does not allow intermediate fractions to be considered as non-polluted. Apart from the fraction (−63; +25 µm), all fractions are polluted above the Cu safety level. The distributions of Co, Cr, Hg, Ni and F^- are much more homogeneous between the different particle size fractions.

Table 5. Mass content distribution and inorganic pollutants level distribution inside NLS sediment compared to the thresholds specified in [42].

		Size Fractions						Maximum Allowable Content *	Safety Level *
		Raw	**(+1.7 mm)**	**(−1.7 mm; +250 µm)**	**(−250; +63 µm)**	**(−63; +25 µm)**	**(−25 µm)**		
Mass distribution (%)		-	31.8	9.5	5.5	15.3	37.9	-	-
Pollutant levels ($mg/kg_{dry\ matter}$)	As	15.4	10.0	14.3	13.8	11.5	25.1	50	100
	Cd	<10	<10	<10	<10	<10	<10	6	30
	Co	<10	<10	15.4	*29.0*	13.2	15.1	25	100
	Cr	103.2	177.9	106.1	110.2	128.8	124.6	200	460
	Cu	**926.2**	**470.5**	**650.8**	**651.7**	*392.8*	**1042.3**	150	420
	Hg	*1.54*	0.9	1.0	0.9	1.1	*2.0*	1.5	15
	Ni	49.7	66.4	49.6	52.3	40.6	69.3	75	300
	Pb	*521.3*	*327.2*	*320.3*	*282.3*	219.6	*584.7*	250	1500
	Zn	*2066.2*	1043.9	*1401.6*	*1281.5*	1045.7	**2418.6**	1200	2400
	F^-	*315.5*	*266.7*	*346.7*	*348.3*	232.5	*391.9*	250	500
	CN^-	7.3	3.1	3.3	2.5	2.2	9.9	5	25

* according to Walloon government agreement of 30 November 1995 [42]. Bold characters: contents above the safety level. Italic characters: contents between the maximum allowable content and the safety level.

3.1.3. Leaching Behaviour

Despite the three sediments already being classified as "B" according to reference [42], a leaching test was carried out on all raw sediments. Leached inorganic pollutant levels were recorded and depicted in Table 6. The leaching procedure follows the EN 12457-2 standard, required in most European projects and in [42]. It has the same objectives as TCLP (Toxicity Characteristic Leaching Procedure, U.S. Environmental Protection Agency Method 1311), which is usually required in the USA and some other countries. EN 12457-2 differs from TCLP as it is a single step batch leaching test. Nevertheless, both procedures give most often comparable results [47,48] with slightly different behaviour according to sample pH or anionic contents [48,49].

Table 6. Leached inorganic pollutant levels for the three studied sediments compared to the thresholds specified in [42].

	Pollutants	**SLS**	**ALS**	**NLS**	**Maximum Allowable Content ***
Levels ($mg/kg_{dry\ matter}$)	As	<0.5	<0.5	<0.5	0.5
	Cd	**0.95**	<0.04	<0.04	0.1
	Co	<0.5	<0.5	<0.5	0.5
	Cr	<0.1	<0.5	<0.1	0.5
	Cr^{VI}	<1	<1	<1	0.1
	Cu	<1	<1	<1	2
	Hg	<0.001	<0.001	<0.001	0.02
	Ni	**1.17**	<0.4	0.47	0.5
	Pb	<0.5	<0.5	<0.5	0.5
	Zn	**42.06**	<1	**9.52**	2
	F^-	<10	13.70	<10	20
	CN^-	<0.01	0.01	<0.1	0.1

* according to Walloon government agreement of 30 November 1995 [42]. Bold characters: contents above the maximum allowable content.

SLS sediment demonstrates a strong leaching behaviour, as cadmium, nickel and zinc leached at concentrations largely above the maximum allowable content. Other pollutants are below detection limits. ALS sediment is cleaner than previous sediment, as only fluorides and cyanides are detected in the leachates, moreover in concentrations lower than the maximum allowable. NLS sediment presents some leaching of nickel (under the maximum allowable content) and zinc (largely above the maximum allowable content). In conclusion, SLS and NLS sediments can be considered as hazardous as some of their inorganic pollutants leached above the maximum allowable content.

These results imply that a large fraction of the dredged sediment could be recovered using a dry deagglomeration procedure, because all sediments are fine-grained. Steps of pure grinding are therefore not necessary; only deagglomeration steps are required.

Regarding the preparation of -63 μm fractions for the development of lightweight aggregates and supplementary cementitious materials, a wet cut at 63 μm allows to obtain a large fraction under 63 μm, as all sediments are fine-grained. However, this fraction is expected to be more polluted in inorganics than the non-treated sediment. This must be kept in mind for beneficial uses.

3.2. Deagglomeration of River Sediments for Incorporation in a Concrete Formulation

The preparation of the river sediments has to meet three main goals to allow their addition into concrete:

- A concrete mixer generally allows material of a maximum 20 mm, namely the maximum size of the mineral granulates. Therefore, any materials, including sediments, must have a particle size below 20 mm. To ensure a good dispersion of the sediment inside the concrete formulation, a much lower maximum size was chosen: first 5 mm and then 10 mm (which is a more common size for industrial screens).
- To increase the contact area between sediment particles and concrete ingredients, the presence of any heterogeneities in the concrete must be avoided.
- To prepare waterway sediment for easier handling by the operators of the concrete plant. It means that the river sediment must be stored in a feed hopper and must be transported to the concrete mixer by conveyor belts.

Moreover, as the sediment will be introduced in a concrete formulation, the moisture content is not a problem. Concrete mixing is a wet process. Nevertheless, the moisture content is an obstacle for deagglomeration. If deagglomeration is hindered by the moisture content, additional drying will therefore be necessary, but only to reduce the moisture content at a sufficient level for the deagglomeration, as the drying process is expensive and will deteriorate the economic balance of the deagglomeration process.

First, several different technologies of deagglomeration were tested. Then, batches of approximately 1 m^3 of deagglomerated sediment were prepared to supply the laboratory work of sediment incorporation into concrete. Finally, after upscaling, a large batch of sediment was prepared from 16 tons of materials.

3.2.1. Preliminary Tests

To choose the convenient technology to deagglomerate the sediment, the first attempts were carried out on the SLS river sediments, previously screened at 5 mm at the Sedisol plant.

Several technologies were tested, among which was the screw feeder. The mechanical action of the screw could impact deagglomeration of dried sediments. Nevertheless, the feed hopper of this screw is too narrow to accommodate large agglomerates (some are larger than 0.5 m). A very large screw feeder would therefore be necessary; nevertheless a sufficiently large screw feeder was not available. Moreover, the flow rate is rather low, and the screw does not allow the processing of large exogenous particles, especially as the screw is a small size model intended for fine developments, such as soil liming, etc. Compared to a concrete mixer, the technology is similar; however, the aim of this study is to reduce sediment agglomerates size to be accommodated into the concrete mixer. Therefore, another technology was tested.

Low rotation velocity technologies were evaluated, such as conventional shredder or lump breaker. Even though these technologies present large flow rates, some disadvantages were observed. Lump breakers are designed to deagglomerate filter-press cakes, therefore fine products with particle size lower than a few millimetres. Therefore, unscreened lagooned sediments cannot be treated in lump breakers. Shredders can break the exogenous particles, but present difficulties to break large blocks if the tooth cannot enter in the agglomerate blocks. These blocks then roll on the tooth without deagglomeration effect.

Finally, grinding technologies with rolls were tested, using a single-roll shredder. This equipment accepts large exogenous particles, the flow rate is sufficient for the objective of a 1 m^3 batch, and the push-piece allows pressing the large blocks against the toothed cylinder. Therefore, roll shredding technologies were used in the following steps.

3.2.2. Preparation of Samples for Laboratory Trials

Direct deagglomeration attempts were carried out on the SLS river sediments with the single roll shredder, without using a calibration grid. Nevertheless, deagglomeration was not fully completed because the water content (29.2%) was too high to disperse sediment particles. This is important, because the aim of the deagglomeration is to increase the contact area between sediment particles and concrete ingredients to allow a good mixing.

Consequently, a passive drying was carried out on the SLS sediment, namely the sediment was dried in the ambient air for two weeks. This step allows decreasing the water content from 29.2% to 17.5%. Deagglomeration of the dried materials allows producing a sufficiently fine fraction of river sediments (Figure 8). A total of 1.5 tons of river sediments were treated this way.

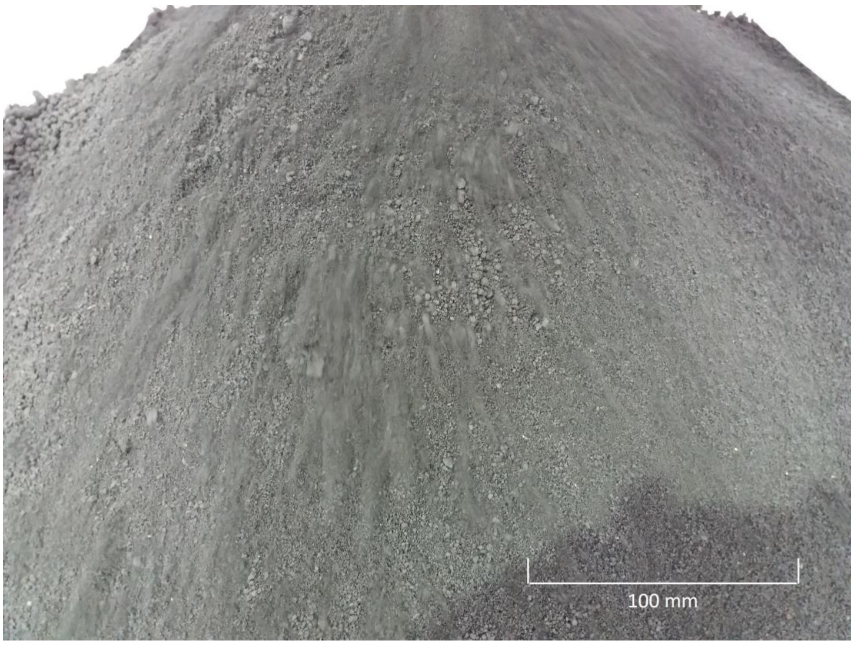

Figure 8. Deagglomerated river sediment.

A sample of the NLS river sediment was treated with the same process. Nevertheless, as observed in Figure 9a,b, this sediment was not previously sieved, and therefore a sieving at 5 mm had to be performed before drying, to extract large elements. This drying allowed decreasing the water content from 28% to 22.7%. This moisture was sufficient to carry out the deagglomeration.

(**a**) (**b**)

Figure 9. NLS river sediment. (**a**) Presence of exogenous like large granulates or medication package; (**b**) presence of granulates.

Two fractions were therefore obtained: a deagglomerated sediment (−5 mm) and a coarse fraction, mainly made up of exogenous and anthropogenic materials (glass, plastic bottles, granulates, etc.). A total of 849 kg of deagglomerated (−5 mm) material was obtained, whereas the weight of the coarse fraction was not negligible (101.6 kg of material).

The ALS sediment (from Ampsin lagoon) was treated by passive drying, deagglomeration (with the single roll shredder) and sieving steps. Figure 10 describes the sequence of the deagglomeration process and Table 7 gives the mass balance of the operation. The step of passive drying allows to reduce the moisture content from 30.9% to 24.2%. The first sieving step at 5 mm recovered approximately one third of the final deagglomerated sediment in the undersize. Most of the sediment was recovered after the first crushing with the single roll shredder followed by sieving. The operation was repeated, and after the second step of crushing and sieving, less than 9% of the total sediment remained agglomerated. The existence of a remaining non-deagglomerated fraction can constitute a slight disadvantage of the process.

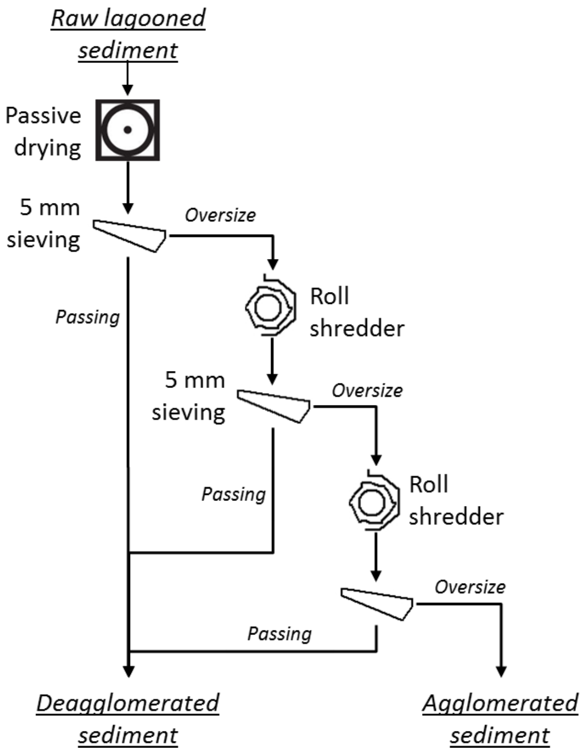

Figure 10. Deagglomeration process for the ALS sediment.

Table 7. Mass balance of the ALS sediment deagglomeration process.

Fractions		Wet Cake Mass (kg)
Wet sediment cakes		725
After partial passive drying		689
Deagglomerated sediment	After initial sieving	217
	After first crushing and sieving	314
	After second crushing and sieving	72
	Total	603
Non-deagglomerated sediment		78

Several batches of deagglomerated sediment were then submitted for laboratory trials to study the concrete formulation. Nevertheless, this process suffers from several drawbacks, which makes it unsuitable for processing larger volumes. These volumes were necessary for one of the final goals of the VALSE project, which is the building of a large bicycle path. The several drawbacks are summarized below:

- Requirement of a further drying step after natural dehydration in the lagoon, with a more advanced technique;
- Sieving at a size of 5 mm, which is less common in dry sieving;
- Presence of a large proportion of final refusal;
- High number of successive steps with similar equipment;
- Low flow rate (0.1 to 0.25 m^3/h);
- Potential wear of the single roll shredder, as this equipment is designed for soft materials, such as plastics or biomass, and not for minerals.

3.2.3. Upscaling and Production of a Large Batch of Sediment

The ALS sediment was chosen for the building of a bicycle path made with sediment-containing concrete. About 16 tons of wet cakes had to be processed and the upscaling required modifications of equipment sizes to shorten processing time and overcome potential drawbacks. Figure 11 presents the upscaled line to produce a large batch of deagglomerated sediment.

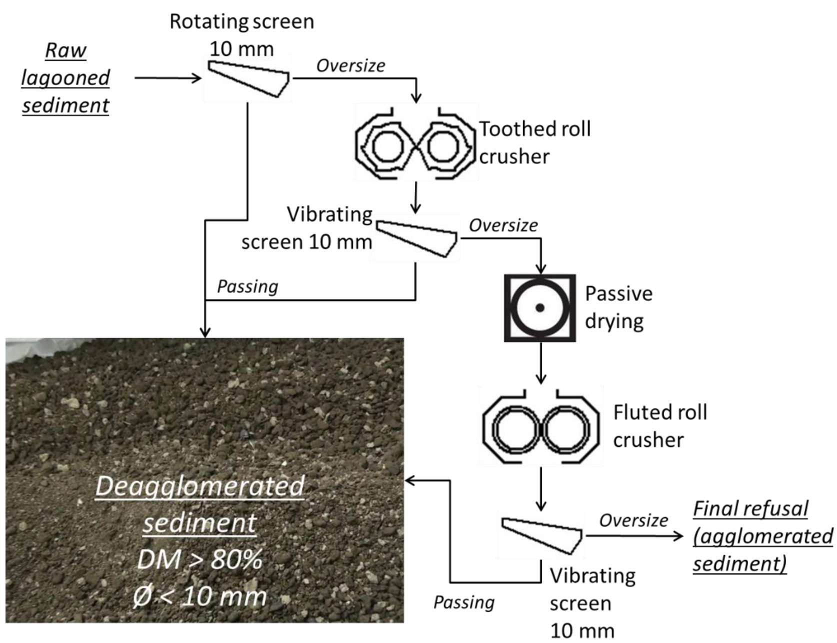

Figure 11. Deagglomeration process for the large batch production on the ALS sediment.

First, the initial further drying step before treatment was postponed after earlier treatments to reduce the space required for drying. Indeed, the passive drying step must be carried out under covered shelters, and its footprint must be optimized.

Second, the ALS sediment was directly screened at 10 mm with a large rotary screen (Figure 12), with a capacity of several tons per hour. About 6.5 tons of deagglomerated sediment were recovered during this first step. The screening mesh was increased because 10 mm is a more common sieve aperture in the mineral industry, and this aperture is still less than the maximum allowed size (20 mm).

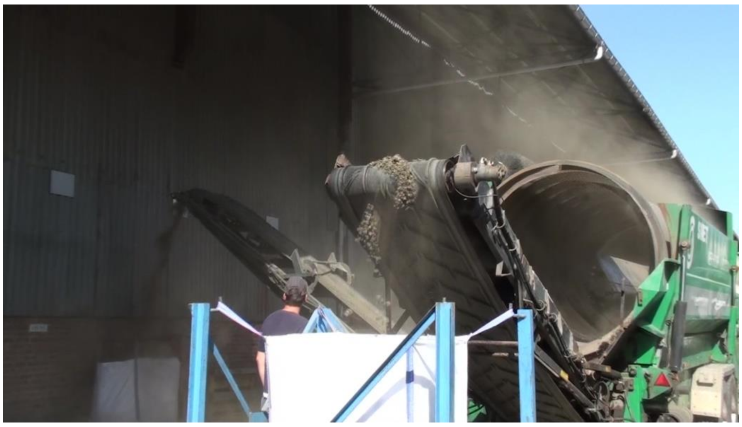

Figure 12. Step of rotating drum sieving.

The crushing steps also have to be fine-tuned, because of the low flow rate of the single roll shredder. A toothed roll crusher replaced the single roll shredder, as each display teeth over their respective cylinders. Moreover, roll crusher technologies are dedicated to mineral materials. Therefore, toothed or fluted cylinders are adapted to the treatment of sediment and no premature wear problems are expected. A treatment line composed of the toothed roll crusher and a vibrating screen with 10 mm aperture panels was implemented, allowing to screen directly the crushed sediment (Figure 13). The efficiency of toothed roll crushers on sediment less than 10 mm is not optimal, hence a large oversize fraction is observed. Nevertheless, the amount of passing fraction (4.5 tons) exceeded by far the amount of oversize. The oversize refusal was constituted of a wet fraction of sediment with dimension close to 10 mm.

Figure 13. Step of toothed roll crushing with 10 mm sieve directly connected (in the back).

The drying step was therefore performed after the first crushing and screening steps, under covered shelters. The moisture content of the sediment oversize decreased from 22.7% to 15.1% in 6 weeks.

The slightly dried fraction was processed again in a treatment line composed of a fluted roll crusher, and a vibrating screen equipped with 10 mm aperture panels (Figure 14). The use of a fluted roll crusher allowed to reduce further the grain size of all sediments below 10 mm, and only large leaves were recovered in the final oversize.

Figure 14. Step of fluted roll crushing (in the back) with the 10 mm sieve directly connected (in the front).

Table 8 gives the mass balance of the operation over the upscaled line. The upscaled line allows to recover a maximum of sediment (only 30 kg of agglomerated sediment after treatment, compared to 13,429 kg of deagglomerated sediment). Most undersize fractions are recovered during the initial screening and after the first roll crushing followed by 10 mm screening.

Table 8. Mass balance of the ALS sediment deagglomeration process.

Fractions		Wet Cake Mass (kg)
Wet sediment cakes		16,612
Deagglomerated sediment	After initial sieving	6523
	After toothed roll crushing and sieving	4456
	After partial drying and fluted roll crushing followed by sieving	2450
	Total	13,429
Non-deagglomerated sediment (final oversize)		30

Flow rate was estimated as 1 ton/h. An estimation of the cost was made on Table 9, with the following hypothesis: 1 €/ton for screening, 5 €/ton for roll crushing and 20 €/ton for passive drying. Processing cost is evaluated to 10.62 €/ton. Among this cost, passive drying cost is the largest and represents almost the half of the operating cost, to process only around 25% of the amount of deagglomerated sediment. To decrease the operating cost, this step, and the two following, may be skipped.

Table 9. Details of operating costs calculation based on the mass balance of the ALS sediment deagglomeration process.

Step	Processed Amount in the Step (ton/ton at the Entrance)	Operating Cost (€)
1. Sieving	1.00	1.00
2. Toothed roll crushing	0.57	2.84
3. Sieving	0.57	0.57
4. Passive drying	0.26	5.19
5. Fluted roll crushing	0.17	0.86
6. Sieving	0.17	0.17
Total		10.62

3.2.4. Verification of Sediment Quality

Sediment quality in terms of pollutant levels was measured and detailed in Table 10. Three samples were analysed: the first one was used for the characterisation, the second one was from the batch prepared to supply material for laboratory trials and the third one was a representative sample from the 13.5 tons prepared for the bicycle path. The aim of this verification was to avoid contamination from an external source; this source could be, for example, the equipment used in the several steps.

Table 10. Pollutant levels (mg/$kg_{dry\ matter}$) for each ALS sample.

	As	Cd	Co	Cr	Cu	Hg	Ni	Pb	Zn	F^-	CN^-
Characterisation	<10	*29.8*	11.5	*207.4*	89.0	0.9	41.6	151.8	967.0	569.2	2.0
Deagglomerated sediment for laboratory trials	14.4	*22.7*	14.0	99.3	93.0	1.0	53.4	232.7	1080.0	*430.6*	n.a.
Large batch of deagglomerated sediment	13.5	*25.7*	14.9	176.1	109.0	0.8	47.6	217.1	1014.5	160.6	n.a.
Maximum allowable content *	50	6	25	200	150	1.5	75	250	1200	250	5
Safety limit *	100	30	100	460	420	15	300	1500	2400	500	25

* according to Walloon government agreement of 30 November 1995 [42]. Bold characters: contents above the safety level. Italic characters: contents between the maximum allowable content and the safety level. n.a.: not analysed.

All pollutant levels are consistent between batches, except fluoride. Fluoride level recorded for characterisation is far above the fluoride level recorded in the large batches. The explanation is the sampling of materials by picking. Many individual samples were taken for each of the three batches and then mixed to obtain a composite. More than 20 samples were collected for each batch, but this was not sufficient to obtain a homogeneous sample regarding fluoride content. Other sampling techniques could have been applied, such as rotary samplers, but given the size of the sample it would have been difficult to apply them.

Cyanides are known as unstable species. The number of steps applied on the treated sediment is large and the delay between characterisation results and the analysis of the large batch is also large. Therefore, cyanide levels may present some inconsistencies and were not analysed.

3.3. Extraction of the −63 µm Fraction to Produce Pozzolanic Materials and Lightweight Aggregates

3.3.1. Separation of the −63 µm Fraction

To achieve this more advanced separation, dry techniques were not adapted. Only wet techniques can achieve this level of particle size classification.

The SOLINDUS pilot platform was used to obtain the −63 µm fractions from SLS and NLS river sediments. Only the five first steps of the pilot presented in Figure 6 were required, namely the scrubbing drum equipped with a trommel, the vibrating screen, the curved screen, the hydrocyclone and the screw classifier.

Anthropogenic materials and granulates were removed from the coarser fraction of river sediments by the scrubbing drum and the trommel (Figure 15), as well as the vibrating screens. Coarse sands (from 2 mm to 250 µm) were extracted by the curved grid and fine sands (from 250 to 63 µm) were classified by the hydrocyclone (Figure 16) and the screw classifier in series. After separation, the −63 µm fraction was dehydrated by using a filter-press.

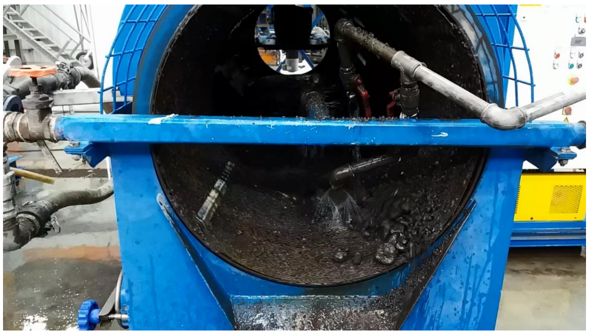

Figure 15. Separation of coarse materials in the rotating drum (trommel).

Figure 16. Hydrocycloning step.

Medium size sand was recirculated in the platform to recover particles finer than 63 µm remaining in the intermediate sand fractions.

The final goal of the operations was to supply 100 kg of −63 µm fraction of each river sediment. This goal was achieved for both SLS and NLS sediments.

3.3.2. Verification of −63 µm Fraction Quality

As observed in Figure 17, both fractions are below 63 µm, with finer particles in the −63 µm fraction of SLS sediment.

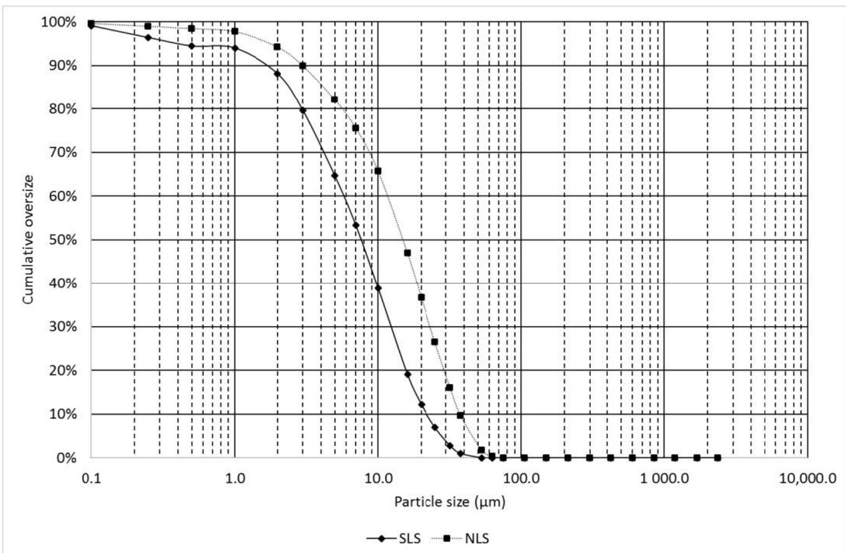

Figure 17. Particle size distribution of the (−63 µm) fractions obtained by size classifications for SLS and NLS sediments on the SOLINDUS platform.

To fulfil requirements to be used as raw materials for pozzolanic materials or lightweight aggregates, the composition in major elements must be analysed and is depicted for both sediments in Table 11. This analysis was carried out by the project partner involved in the valorisation of sediment into SMCs and lightweight aggregates.

Table 11. Major oxides composition (%) for each −63 µm fraction provided to study sediment incorporation into SMCs and lightweight aggregates.

−63 µm Fraction	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	Na_2O	SO_3	P_2O_5
SLS	40.8	13.9	10.0	2.6	1.1	2.1	0.5	1.0	1.1
NLS	32.2	8.2	4.3	10.8	0.9	1.6	1.9	4.0	1.4

The suitability of fractions below 63 µm was discussed in reference [15] for recycling in SCMs and in reference [26] for valorisation in lightweight aggregates.

The content in CaO is higher for the NLS sediment, compared to SLS sediment. Combined with an XRD analysis, Kazemi-Kamyab et al. [15] found a higher content in calcite. The combined presence of calcite with potentially less-reactive clay minerals is considered promising as they may react during calcination to form a reactive amorphous Ca-enriched aluminosilicate compound.

Thanks to the major oxides analysis, Peys et al. [26] forecasted that the SLS −63 µm fraction can be valorised in lightweight aggregates, but not the NLS −63 µm fraction. In fact, the SLS −63 µm fraction stays in the bloating region of the Riley diagram (ternary diagram $SiO_2/Al_2O_3/Flux = Fe_2O_3 + CaO + K_2O$) but not the NLS −63 µm fraction. A similar prediction was carried out using thermodynamic simulation. These forecasts were confirmed when lightweight aggregates were produced at laboratory scale.

4. Discussion

The first motivation for dredged sediment's beneficial use is the necessity of dredging operations for sustainable water transport and for rivers and ports management, including flood prevention. These operations result in the production of huge volumes of dredging that would be considered as waste if no reuse option is considered. They would be the second biggest waste flow at the EU scale [1], and probably anywhere else.

Among the many options for reuse, sediment valorisation as secondary raw materials, and especially as a substitute to primary raw materials from extraction (sand, clay . . .), fits the objectives of the circular economy [4]. Among the biggest users of such raw materials are civil engineering works and concrete production.

The main reason for incorporating sediments inside concrete is the large volume of concrete used in the world: 14 billion m^3 in 2020 [50], along with the large volume of available dredged sediment. However, direct replacement of primary minerals by sediments in concrete production is rarely possible, as the heterogeneity and engineering properties of raw sediments do not fit concrete specifications. In order to use dredged sediments in a concrete mix, a processing step has to be considered.

The incorporation at industrial scale of sediment inside concrete poses several challenges. First, the sediment must be easily handled by operators. It must also present a particle size below 20 mm to enter the concrete mixer and to ensure an adequate dispersion of the particles, with the additional constraint of not decreasing excessively the moisture content. The matrix chemistry of sediments needs also to match as much as possible that of primary raw minerals used for this purpose. Furthermore, the contaminants present in sediments must not hamper their safe valorisation. Leaching tests are therefore a critical part of the evaluation process, as immobilised contaminants are no longer a threat.

Using dredged sediments without any processing apart from natural or assisted dehydration would result in major operational difficulties and in poor engineering properties of the concrete. Raw or dehydrated sediments are therefore only suitable for bulk civil engineering applications, such as dikes, noise walls or landscaping mounds.

The application of common mineral processing techniques such as coarse sieving, roll crushing and natural drying, with a correct sequence of steps, allows to face the challenges presented in the above paragraphs. Roll crushing technologies were chosen to process wet solid materials. Sieving is sufficiently coarse to accommodate the moderately wet sediment issued from a lagoon. Natural drying can be applied to treat the remaining sediment.

Moreover, facing the above challenges, the process developed in this article is original and adapted to an industrial environment. In several articles about beneficial uses of sediment inside mortars or concretes [5–12], sediment pre-treatments are not described or are described briefly. Table 12 gives an overview of the applied pre-treatment of some references. All of them are applied at laboratory scale and most of them consist of sieving and drying steps. These steps are quite easy at laboratory scale but are less convenient or too expensive at industrial scale.

Table 12. Pre-treatment applied by several authors on sediment before incorporation into mortars or concrete.

Reference	Applied Pre-Treatment.
[6]	40 °C drying and grinding below 80 µm.
[7]	Washing (desalination).
[8]	3 mm dry sieving and 105°C drying.3 mm dry sieving, washing (desalination), dewatering by filter-press, 105°C drying and 63 µm dry sieving.
[9]	60°C drying, hand and jaw crushing, and 8 and 3 mm dry sieving.
[10]	20 mm dry sieving and weathering.45 °C drying before use.
[11]	Natural drying, wet sieving at 80 µm and drying of the refusal at 80 °C.
[12]	Natural drying.

Dry sieving at mesh above 1 mm is quite easy at industrial scale, but dry sieving at 63 or 80 µm is more difficult and non-economical for a large volume material like concrete. Drying is expensive at the industrial scale, even at low temperature. Moreover, sediments will be incorporated in a wet material (fresh concrete); therefore, a complete drying is not necessary. Sediment agglomerates will also be dissolved inside the concrete; therefore, a complete deagglomeration is not needed. The studied treatment in the present paper allows avoiding difficult steps of fine sieving or thermal drying. This allows to reduce the operating cost to around 10 €/ton.

This work allows to define a process to accommodate sediment inside concrete. This process allows to deagglomerate the sediment blocks below a size which can enter inside an industrial concrete mixer. To allow this deagglomeration, only a decrease in the moisture level is necessary (till 15 to 20%). Sediments will therefore be present in the form of particles with some agglomerates lesser than 10 mm.

The other way to prepare a sediment is the wet cutting at 63 µm. This size classification will be more expensive; therefore, the beneficial use of end products must be more valuable, as investigated by Kazemi-Kamyab et al. (supplementary cementitious materials; [15]) and Peys et al. (lightweight aggregates; [26]), who used the prepared materials described in the present paper.

Moreover, as observed during the characterisation, the heavy metal pollutant contents are concentrated in the finest fraction. Therefore, this pre-treatment is more intended for thermal beneficial use, allowing the vaporisation or the oxidation of organic pollutants and the stabilisation of the heavy metals.

5. Conclusions

Mineral processing techniques are adapted to the preparation of river sediments intended for raw material beneficial uses. This can be achieved through dry or wet processing, the choice of techniques depending on the goal to be achieved.

Large-scale incorporation of river sediments into the feed formulation of a concrete plant requires specific sediment preparation procedures, among which are dry sieving, natural drying and deagglomeration using soft grinders. Adaptation of mineral processing techniques was necessary to achieve the goal of the production of large batches. The right tools, namely toothed and fluted roll crushers, were chosen to enable treatment of a large batch of sediments with good recoveries. The procedure was also tailored to treat a large amount (16 tons) of sediment. Deagglomerated sediment was therefore ready for integration into the mixer of a concrete plant.

River sediments can also be used as raw materials for lightweight clay aggregates and pozzolanic materials. It requires the extraction of a fine fraction (−63 µm), which can only be achieved by wet classification techniques. As often observed, the extracted fine fractions are more polluted with heavy metals than the raw sediment. They actually concentrate the heavy metal load, and this may be desirable if the objective of processing is to reduce the volume needing to be landfilled. Nevertheless, the used valorisation scheme uses a thermal process which can trap the pollutants in the material and stabilise them.

In addition to contamination, the matrix composition is also an important point for recovery. According to major oxides content, the SLS sediment had a better suitability for recovery into lightweight aggregates than the NLS sediment, while the NLS sediment could be preferably recovered as SCMs, thanks to its high content in calcium oxide.

This approach contributes to the circular economy objectives of countries and regions by reducing the demand for primary minerals and reducing as far as possible the volume of sediments to be landfilled.

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Conflicts of Interest: The authors declare no conflict of interest.

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