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Reuse potential of dredged river sediments in concrete: Effect of sediment variability

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Abstract

Dredged river sediments may potentially be reused as aggregate in concrete production. The variability of dredged sediments has been quantified by measuring their concentrations of heavy metals, several distinct pollutants, specific granular fractions and organic content at various locations in the Seine River watershed over three years (2015-2017). It has been shown that the sediment deposit does not significantly change from one year to the next, while the organic content, which delays cement hydration, concentrates in the finest fraction removable by sieving. Moreover, 30% of sediment volume is mainly sand and readily reusable in the form of concrete aggregate. Various sediments have thus been sieved to coarse aggregates, sands and fines in order to formulate concretes. Substituting 30% of aggregate volume by the resulting coarse aggregates or sands, once depleted of silt and organic matter: marginally affects hydration, extends setting time to just under 3 hours, decreases compressive strength by 10%, and increases shrinkage strain by 15%. In contrast, the finest part of the sediment significantly alters these properties, owing to its soluble organic matter and silt contents.

Keywords: Sediment variability, Concrete, Hydration, Strength, Shrinkage.

1. Introduction

In the Paris Region (Ile-de-France), large amounts of dredged sediment are generated in order to prevent flood risks and maintain a sufficient navigation depth. Over the three-year study period, from 2015 to 2017 inclusive, these operations dredged a volume of 413,000 m^3 of sediment from the rivers, canals and tributaries within the Paris Region and its surroundings (DTBS, 2016, 2017, 2018), all of which are managed by the Territorial Directorate of the Seine River Basin (DTBS), as part of VNF (France's Navigable Waterways Authority). These sediments are currently managed according to the following breakdown: quarry filling (38%), transit site (14%), agricultural land adjustments (7%), treatment before reuse or storage (6%), sorting before reuse or storage (6%), filling behind sheet piles (4%), composting (4%), and leveling along embankments (1%). Moreover, the remaining 20% of these sediments are conveyed to inert waste storage facilities (i.e. the ISDI sector, (DTBS, 2018)), at a cost of between 5 and 11 euros/ton (ADEME, 2012). For the French Navigable Waterways Authority, the ISDI sector must reach at least 200,000 euros/year within the Paris Region. Although these dredged sediments are legally treated as waste, 90% of their volume dredged in 2017 was inert (DTBS, 2018; Decree-December12, 2014). Furthermore, an ecotoxicity analysis enables classifying sediments dredged in 2015, 2016 and 2017 as 100% non-hazardous, according to the HP14 criteria (Council-EU, 2017; INERIS, 2016) and based on the French S1 concentration thresholds (Decree dated August 9, 2006 (Decree-August9, 2006)). The quality of these sediments thus enables managing deposits for more beneficial purposes.

Many international studies indicate various beneficial reuses of dredged sediments as a raw material in construction, namely: road construction (Kamali et al., 2005, 2008; Scordia, 2008), cement production (Aouad et al., 2012; Benzerzour et al., 2017; Dalton et al., 2004; Dang et al., 2013; Du and Pang, 2018), and aggregate replacement for mortar or concrete manufacturing (Agostini et al., 2007; Ben Fraj et al., 2012; Limeira et al., 2011; Mymrin et al., 2017; Said et al., 2015; Wang et al., 2017, 2018). Reusing sediments as concrete aggregates offers both economic and environmental prospects. Hence, the quality of the Seine watershed dredged sediments is such that concrete

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aggregates could be replaced without performing costly treatments. Nevertheless, these sediments contain organic matters, shells and fines that may affect the concrete properties. For instance, organic matter is known to delay setting and hinder the development of cement paste strength (Beddaa et al., 2019; Chen and Wang, 2006; Clare and Sherwood, 2007; Saride et al., 2013; Tremblay et al., 2002). Moreover, shells reduce concrete strength owing to their flattened shapes and poor adhesion to cement paste (Martínez-García et al., 2017; Nguyen et al., 2013b, 2017; Rica, 2017; Yang et al., 2010). Consequently, standards have limited shell content to 10% per weight of aggregates (EN12620+A1, 2008). The fine content of sediments also affects cement paste properties: fines and clay reduce workability due to their specific surface area and water demand, to such a point that both strength and durability could also be affected (Buth, 1967; Norvell et al., 2007; Yalley and Sam, 2018).

River sediment aggregates could be depicted as a naturally sourced or recycled material. As a result, their variability is to be addressed: a statistical analysis is presently proposed at an unprecedented scale, thus enabling a classification of aggregates. Since these aggregates are handled near navigable waterways, where some concrete batching plants are located, their use would reduce both amount of waste and environmental footprint related to transportation. Numerous new experimental results are therefore reported and discussed to enable a cleaner concrete production, by making use of these aggregates and matching durability and performance criteria. Data stemming from the 2015, 2016 and 2017 dredging campaigns specific to heavy metal content, organic matter content and size distribution are analyzed to automatically classify sediments using a K-means algorithm. Next, particular dredging points are selected and corresponding sediments sieved into coarse aggregates, sand and fines for substitution into conventional concrete aggregates. Lastly, by monitoring the heat released through cement hydration, the compressive strength and shrinkage strains of concrete will either favor or refute the volume substitution of conventional aggregates by these sediment aggregates.

2. Methodology

This section begins with a presentation of the methods used to characterize the sediments dredged in the Seine River watershed in terms of pollutant content, organic matter content and particle size distribution. A statistical analysis of the resulting database helps classify these sediments. The effect of various sediments on concrete hydration, strength and shrinkage is then experimentally quantified.

2.1. Deposit characterization

The database, provided by VNF, reports more than 50 properties characterizing a sediment, from one dredging point to another for 135, 120 and 102 dredging points in 2015, 2016 and 2017, respectively (DTBS, 2016, 2017, 2018) for a network consisting of 1,400 km of waterways. Some database fields have been selected in order to perform the proposed variability assessment; these fields either ensure that the sediment is clean enough to be legally reused or else provide insight into the effect of sediments on concrete properties. On the one hand, some dredged sediments have proven to be non-inert, as defined in (Decree-December12, 2014), mainly due to their amount of total hydrocarbons (THC) or leached antimony (Sb). While on the other hand, a few dredged samples fail to comply with the S1 thresholds (Decree-August9, 2006) due to their lead (Pb), zinc (Zn) or mercury (Hg) contents; nevertheless, they are still classified as non-hazardous since all HP14 criteria are being respected. The PCB and PAH pollutants, given their ubiquity and persistence, have also been selected owing to their adverse effects on human health (Ontiveros-Cuadras et al., 2019). Furthermore, the organic matter content and weight fractions of granular classes (fines ($<50\mu\text{m}$), sand ($50\mu\text{m}-2\text{mm}$), and 2mm sieve non-passing fraction) are fields offering a potential correlation with concrete properties. Table 1 compiles the fields considered for the proposed study, as well as the corresponding ISDI thresholds for inert storage facilities and S1 thresholds.

2.1.1. Parametric distribution

Univariate, lognormal and uniform Gaussian distributions are adjusted to the observed distributions of each field over the years 2015, 2016 and 2017. The parameters of the Gaussian and log-normal distributions (mean and standard deviation) are set according to non-biased estimates. The extrema of the uniform distribution correspond to those of the observed attribute. Next, a Kolmogorov-Smirnov test is performed and its parameters calculated. The resulting D-value describes the gap size between the observed and estimated distribution functions. The associated p-value signifies the probability of obtaining such a gap if the measurements are derived from the fitted distribution. A high p-value means that the observed measurements could stem from the identified distribution (Scipy, a). Let's note that these distributions are adjusted as if the various fields were independent of one another, although this assumption can be challenged by computing the actual correlation coefficients.

2.1.2. Correlation coefficients

To assess how one parameter X_i evolves with respect to another X_j , the Pearson correlation coefficient $\text{Corr}(X_i, X_j)$ is computed on the three-year database. Due to the some missing organic matter content values, these cross-correlation coefficients are valued using 188 dredging points (63, 65, 60 dredging points for 2015, 2016 and 2017 respectively). The Pearson correlation coefficient value varies between -1 and 1; it equals: -1 in the case whenever one of the parameters is a decreasing linear function of the other, and 1 whenever a parameter is an increasing linear function. The p-value associated with the sample Pearson correlation coefficient is also calculated; this value depicts the probability that an absence of correlation leads to an estimated correlation equal to or greater than the one obtained. A low p-value reflects a strong presumption that the random variables observed are linearly correlated and therefore depend on one another. The correlation coefficient and associated p-value have been calculated using the `scipy.stats.pearsonr` function (Scipy, b).

2.1.3. K-means algorithm

The K-means algorithm is automatically applied to classify the various sediments into groups. The number of clusters is predetermined. The algorithm seeks to find the center of clusters that minimize the sum, over the given set of points, of distances to the nearest cluster center (MacQueen, 1967; Steinhaus, 1956). As a result, the outcome of the method depends on the metric defining the distance between points. More specifically, this distance must presently balance the differences in pollutant concentrations, the differences in sieve fractions and the organic matter amounts. To this end, a gauge is introduced for each parameter, and measured values are divided by their corresponding gauge prior to applying the Euclidian norm between scaled points. For pollutant concentrations, this gauge is simply defined as the smallest corresponding threshold (ISDI or S1); otherwise, the highest value encountered is considered as the gauge. The relevance of clustering is closely tied to the definition of the chosen distance. This algorithm is implemented using `sklearn.cluster.KMeans` class (Scikit-learn).

To represent all dredging points and thus maintain as much information as possible in the database, an estimate of the missing organic matter content values becomes necessary. To this end, the K-Nearest Neighbors (KNN) algorithm has been applied, and the missing value is set equal to the average of the value known for the k nearest neighbors (Altman, 1992). The number of neighbors presently considered is set to 5. To pick meaningful nearest neighbors, the distance between two samples k and l is valued as:

$$d(k, l) = \sum_{X_i \in (\text{Parameters})} |\text{Corr}(X_i, OM)| (X_i^k - X_i^l)^2$$

where OM is the field describing the organic matter content and $\text{Corr}(X_i, OM)$ is the correlation between field X_i and organic matter content, as computed in *Section 2.1.2*. Since the number of points is relatively limited, a brute-force approach is applied: the distance between the queried point and all other points in the database is computed.

2.2. Sediment-based concrete characterization

To evaluate the effect of sediments on concrete properties, 19 samples were chosen among the 102 locations dredged in the Seine River watershed during 2017. Among these samples, 8 are mainly sandy and contain less than 5% fines per weight of sediment, while the other 11 samples are visibly sludges. The sandy sediments are dried and sieved into granular classes, as reported in Table 2. The sandy fractions of these sediments define 8 sediment sands (SSs) to be substituted for conventional sand. Moreover, 2 sediment gravels (Gs) were selected among the eight coarsest fractions, as the other six obviously contained over 80% by wt of shells, slag or wood parts. The sludges were dried and easily crushed to agglomerates passing through a 80 μm sieve (Fines Fs) before being incorporated into the concrete. The treatment merely consists of drying, sieving and, optionally, slight crushing to minimize both costs and the environmental footprint. Before studying the effect of sediment incorporation on concrete properties, an exhaustive environmental and physical characterization of the 21 sediment samples (11 fines < 80 μm , 8 sands 80 μm - 4 mm and 2 coarse aggregates 4 mm - 20 mm) was conducted.

2.2.1. Environmental characterization

The environmental characterization of dredged sediments, including the content of heavy metals (Pb, Zn, Hg and Sb), PCBs, sulfates and organic matter is given in Tables 3 and 4 for the 11 fines samples and 8 sandy samples, respectively. Since the amounts of pollutants are measured on the sediment passing through a 2-mm sieve, sediment gravels are considered to be clean. It is shown that sludges contain more heavy metals and PCB than sands. Indeed, sludges are mainly dredged in channels, locks and areas where the water stream is slower. Furthermore, these locations correspond to urban or former industrial areas where water stagnation prevents pollutants from

being leached. For both granular fractions, the amount of sulfate measured remains very low compared to the recommendations listed in (EN12620+A1, 2008). As regards organic matter content, not only do the fines samples exceed the sands, but the organic matter content of the fine part ($< 80 \mu\text{m}$) of the very same original sand sediment is greater. This finding may be due to a concentration of organic matter in the fine part of sediments. Consequently, the fine fraction of sediments contains a higher amount of organic matter than the other granular classes. Since organic matter is known to delay the setting, hydration and the development of compressive strength of concrete (Beddaa et al., 2019; EN12620+A1, 2008); these properties are expected to be altered as organic-rich sediments are substituted for conventional concrete aggregates.

2.2.2. Physical characterization

The physical properties of sediment samples have been compared to those of conventional aggregates (alluvial aggregates from the Ormes Quarries, near Bray-sur-Seine). First, the particle size distributions of the sand and coarse aggregate sediments were determined by means of dry sieving, according to European Standard (EN933-1, 2012) (Fig. 1). The size distribution of the sediment coarse aggregates (4 - 20 mm) is similar to that of conventional coarse aggregates, whereas except for SS1 and SS3 (which feature distributions similar to those of conventional sand) the other categories are significantly finer. Second, the pycnometer method was applied to measure the density and water absorption for sands or coarse aggregates (Table 5), in accordance with European Standard (EN1097-6, 2014). However, the water absorption of fine sediments originating from sludges could not be evaluated by means of pycnometry. All dredged sediments were lighter and displayed greater absorption than the corresponding conventional aggregates, except for sand SS1. The oven-dried sediment density often dipped below 2.2 g/cm^3 : the sediments are considered as lightweight aggregates according to the definition provided in Eurocode Section 11, Part 1.1. The sediment sands tend to be finer than a typical sand, which partially explains their lower density and higher rate of absorption. In contrast, the higher absorption of sediment coarse aggregates is likely induced by their content of porous impurities, such as shells and wood pieces. In addition, the shell contents of coarse aggregates were evaluated according to Standards (EN933-7, 1998) and reported in Table 6. Shell species occurring in dredged sediments were determined to be *Corbicula*, *Dreissena* and *Viviparus* (Fig. 2). *Corbicula* and *Dreissena* are common in navigated waterways but considered as invasive in France because they compete with native mollusks (Bouquerel, 2008; Marescaux and Doninck, 2010), such as *Viviparus* (Tachet et al., 2000). The proliferation of *Corbicula* and *Dreissena* can block industrial water intake or impede the operations of locks as a result of their density (Bouquerel, 2008), thus rendering dredging essential. Moreover, flakiness was measured according to European Standard (EN933-3, 2012) and reported in Table 6; the conventional coarse aggregates proved to be flaky and rather flat. So, even though sediments contained a considerable quantity of shells, their flakiness index remained lower than that of conventional aggregates, and the shape of coarse sediment aggregates did not affect the slump of fresh concrete or promote segregation.

2.2.3. Concrete mix design

The cement used for this study is Portland cement type CEM I 52.5 from Calcia; it mainly contains clinker (91.3% by weight), gypsum (4.9% by wt) and limestone (3.8% by wt) (Table 7). For the control concrete, alluvial aggregates from the Ormes Quarries are used (their properties are listed in Tables 5 and 6). The required slump remains within the range of 16 - 21 cm, which is typical of a plastic pumpable concrete. As regards the concrete incorporating sediments, conventional aggregates were substituted at 30% by volume with sediments. More specifically, both fines (from F1 to F11) and sands (from SS1 to SS8) replaced 30% of conventional sand (CS) volume by maintaining the same aggregate volume in order to produce concretes CF1 to CF11 and CS1 to CS8, respectively. In other mixes, sediment gravels G1 and G2 replaced 30% by volume of the conventional coarse aggregates (CCA) incorporated into the reference mix. Table 8 lists the quantities of various ingredients composing 1 m^3 of concrete for all mix designs. The total water quantity is raised for those aggregates featuring increased absorption in order to yield comparable slump values.

Using 30% or even less as a substitution rate is economical from a sediment management point of view because of the limited amount of sediments being dredged in the Paris Region (less than $200,000 \text{ m}^3$ per year). Such a substitution rate offers a greater chance to observe sediment effects on concrete properties that may be neglected at lower rates.

2.2.4. Fresh concrete

According to European Standard EN12350-2 (EN12350-2, 2012), slump values are measured using the Abrams cone for all mixes. The relative density values of concrete, reported in Fig. 3, are computed by weighing three

times the 11 cm × 22 cm cylindrical samples cast for compressive strength tests.

2.2.5. Hydration

The heat released by cement hydration is measured by means of semi-adiabatic calorimetry tests (i.e. the Langavant method), according to (EN196-9, 2010). Fresh concrete is poured into an insulated calorimeter, and the changes in temperature induced by the heat released due to hydration are monitored and recorded every 10 minutes for 5 days. The calorimeter heat losses are then calibrated and the heat capacity of the sample estimated so as to quantify the heat released by cement hydration reactions starting from the recorded temperatures.

2.2.6. Compressive strength

The compressive strength tests were carried out according to European Standard EN12390-3 (EN12390-3, 2012) on cylindrical specimens 11cm x 22cm in dimension. The samples were demolded 24 hours after being cast, stored in water and then loaded at a later age, i.e. either 3 or 28 days. The reported compressive strength value for a given mix is based on compressive tests performed on 3 samples from the same batch loaded at the same age.

2.2.7. Shrinkage

The mass loss and total shrinkage strain of the considered concretes were measured on $7 \times 7 \times 28 \text{ cm}^3$ prismatic specimens, as required by European Standard (EN12617-4, 2002). The environmental conditions of the storage room are set at 20°C and 50% relative humidity. Shrinkage strains are measured by means of a retractometer calibrated against an INVAR rod before each measurement. The reported shrinkage strains are averaged from 3 measurements recorded on 3 different samples of the same concrete specimen.

3. Results and discussion

3.1. Statistical results

3.1.1. Classification of distributions

Fig. 4 presents the cumulative distribution functions of selected fields of the sediment database for each year. The sediments dredged in 2017 feature slightly smaller amounts of pollutants, a result likely due to the floods that occurred at the end of 2016; also, changes in distributions from one year to the next are hardly significant. Consequently, the sediment dredged in the Seine River watershed could be globally seen as stable. Regarding the deposit properties, just over 10% of the dredging points are non-inert by virtue of exceeding the ISDI thresholds of Sb and THC. Over 95% of dredging points satisfy the S1 threshold for heavy metals. This same observation can be made for the concentrations of PAH and PCB pollutants. Since heavy metals are known to affect cement hydration and strength development (Dalton et al., 2004; Kurdowski, 2014), comparing the heavy metal contents in sediments to those occurring in typical cement is essential. According to (Kurdowski, 2014), the heavy metal content in industrial clinker can be as high as: 371 mg/kg for Pb, and 3,069 mg/kg for Zn. The heavy metal content in standard German cements ranges from 2-200 mg/kg, 20-450 mg/kg and 0.02-0.35 mg/kg for Pb, Zn and Hg, respectively (VDZ, 2002). Above 90% of dredged sediments display negligible heavy metal concentrations compared to conventional cements; their effects on cement paste properties are therefore also negligible. With respect to particle size, 50% of the dredging points contain less than 40% fines by weight ($< 50 \mu\text{m}$); hence, a considerable amount of dredging sediments could easily be reused as aggregates. Moreover, more than 70% of samples contain less than 5% (wt) of organic matter, which favors the reuse of sediments dredged in these locations. On the whole, the Paris Region deposit seems to be clean and valuable. Distributions are fitted to the observed cumulative distribution of individual fields whose smallest D-value is reported in Table 9, along with the associated p-value. These results show that all distributions observed over the three study years would be difficult to model by either the normal, lognormal or uniform distribution. Indeed, the p-values corresponding to these distributions are less than 0.05.

It should be noted that the parametric distribution does not account for the volume being dredged at each dredging point; furthermore, it is implicitly assumed that the fields remain independent of one another. This assumption however is to be challenged given the correlation coefficients identified in the next section.

3.1.2. Correlation coefficients

The correlation coefficients reported herein necessitate an associated p-value being less than 0.01. Table 10 shows the symmetric correlation matrix, whereby the part above the diagonal corresponds to the correlation coefficient values while the part below corresponds to the p-value. The main conclusions drawn from this correlation matrix are as follows:

- The correlation coefficients between heavy metals are very high, producing values as high as 0.92, 0.83 and 0.82 for Pb-Zn, Pb-Hg and Zn-Hg, respectively. These results are consistent with an anthropogenic origin of pollutants, stemming from both industry and transportation uses. The areas surpassing the S1 thresholds are in fact mainly located downstream of cities, in channels and near locks, where the flow rate is limited.
- The PCB and PAH concentrations are not correlated with one another. No significant correlation has been found between PCBs and PAHs, which suggests that PCBs and PAHs stem from different sources.
- The correlation between the main set of parameters used to classify dredged sediments as non-inert (i.e. THC and Sb) is very strong, with a coefficient of 0.72. Hydrocarbons (THC) is strongly correlated with both heavy metals (Pb, Zn and Hg) and PCBs. The presence of these pollutants may therefore be due to the same origins.
- Regarding the particle size distribution, the amount of fines ($< 50 \mu\text{m}$) is, logically, negatively correlated with sand amounts ($50 \mu\text{m} - 2 \text{mm}$), the sample Pearson correlation coefficient is -0.69.
- Lastly, the amount of organic matter is positively correlated with the fines amount, yet negatively correlated with sand and the amounts not passing the 2-mm sieve. The correlation coefficient values are 0.55, -0.52 and -0.41 for the organic matter content with fines, sand and 2-mm sieve retention, respectively. Consequently, the finer a sediment, the higher its organic matter content.

3.1.3. Sediments classification

Given the strong correlations between the various fields of the sediment database, only three fields could be selected out of the first 11 fields. The THC content, weight fraction of fines and organic matter content depict the pollutant contamination, particle size and amount of organic matter, respectively. The K-means clustering is therefore limited to these 3 fields. Since the deposits over the last three years have proven to be 100% non-hazardous (DTBS, 2016, 2017, 2018) and THC is strongly correlated with Pb, Zn, Hg and PCBs, the high or low concentrations of heavy metals and PCBs can be deduced from THC concentration. Furthermore, since the concentrations of Sb and leachable THC are highly correlated, THC alone is capable of globally summarizing the chemical activity of the sediment. The deposit is nearly 100% inert with respect to PAHs and its contamination tends to decrease within the Seine River basin (Lorgeoux et al., 2016). Lastly, the data on granular fractions are limited to fine content given the importance of this information with respect to aggregate particle size. These data have been chosen to partition the samples into three clusters automatically defined by the K-means algorithm and displayed in Fig. 5. The group in green, which represents 32% of the total deposit volume, comprises the cleanest samples, which feature very low THC, fines and organic matter contents. Consequently, reusing these sediments as aggregates requires no treatment. The blue group contains the samples rich in fines (i.e. greater than 30% wt) and organic matter. These sediments occupy 62% of the deposit volume, but the presence of fines and organic matter can limit their reuse in concrete. Nevertheless, a significant fraction of these sediments can still be potentially reused as concrete aggregate, with a simple sieving to remove the fines and a significant fraction of the organic matter. Indeed, the organic matter is mostly concentrated in the finest fraction. The red group, which represents just 6% of the deposit volume, comprises the non-inert ($\text{THC} > 500 \text{mg/kg}$) yet non-hazardous samples. Most of its sediments contain significant amounts of fines and organic matter. This section has shown that the deposit contains a large volume of mainly sandy sediments that offer a good alternative to conventional aggregates. Most of the deposit however has a significant fine particle content. Although simple sieving discards most of the smallest particles, it does generate a large volume of fines that need to be managed. The purpose of the next section is to evaluate the practical consequences of partially substituting coarse aggregates, sand or fines stemming from dredged sediments for conventional concrete aggregates and sands.

3.2. Experimental results

3.2.1. Fresh concrete

The fresh concretes based on sand or coarse aggregates from sediments feature a slump similar to that of the control concrete (CC), provided that the same effective water-to-cement ratio has been considered. More specifically, the absorption water of aggregates is measured and added to the mix so as to produce saturation. The slump value for all concretes lies between 16 and 18 cm. Adding water to saturate the aggregate does ensure that the effective

volume of the cement paste roughly remains unchanged. Furthermore, the differences in size distribution and shape are not sufficient to alter rheology given that sands and coarse aggregates stemming from sediments are being considered. Water has been added to reach the same slump value whenever a fine sediment fraction is substituted for sand. The water demand of the fine fraction is in fact much higher than that of conventional sand, owing to both the smaller sizes and amounts of clay and organic matter. Raising the water/cement ratio enables reaching the slump value of the reference mix (Ayodele and Ayeni, 2015; Olusola et al., 2012; Norvell et al., 2007; Yalley and Sam, 2018). The amount of added water is indicated in Table 8.

Fig. 3 shows the unit weights of the various fresh concretes. In general, the unit weight of sediment-based concrete is less than that of control concrete. While the unit weight of the control concrete is 2.48 t/m^3 , that of the sediment-based concretes ranges from $2.42 - 2.44 \text{ t/m}^3$, $2.35 - 2.46 \text{ t/m}^3$ and $2.31 - 2.41 \text{ t/m}^3$ for the concretes based on coarse aggregates, sands and fine sediments, respectively. According to Table 8, such a difference in unit weight could not be explained by the low sediment density but instead attributed to the added water.

3.2.2. Hydration

Fig. 6 and Table 11 suggest that all concrete samples have reached a comparable degree of hydration since the total heat release does not vary substantially from one concrete to another. This result is mainly due to application of the same w/c ratio value. Moreover, these results underscore that the sediment fines do not generate any pozzolan effect. European Standard (EN12620+A1, 2008) limits the incorporation of aggregates containing organic matter or other substances to such a proportion that the aggregates cause a change in the setting time, but not to exceed a 120-min increase. Except for S6, the incorporation of coarse aggregates and sands originating from sediments at rates of up to 30% by volume fully meet the requirements of this standard. Nevertheless, concretes based on fine sediments show a significant delay in the peak heat flow (between 3.5 and 18 hours) compared to the control concrete. In contrast, the delay in concrete composed of sediment sand or coarse aggregates remains shorter than 3 hours and comparable to that of the reference. The organic content of river sediment is indeed partially composed of fulvic and humic acids (Chen and Wang, 2006; Shneider, 2001). These humate substances are capable of adsorbing on cement particles and retarding the hydration process. Soluble humate substances can adsorb on cement particles and extend this delay to several days. More precisely, the delay depends on the amount of soluble humic substances per weight of cement (Beddaa et al., 2019). From Table 3, the delay in the main peak is not proportional to the rate of organic matter. For instance, the amount of organic matter in CS7 (8.6%) is more than twice that of concrete CF11 (3.44%), while the latter induces a longer delay. In fact, only a portion of the measured organic matter, i.e. the humic substances (humic acid and fulvic acid), is responsible for delaying the hydration kinetics. Other organic components, such as humine, are not soluble, do not significantly interact with the pore solution and therefore likely to exert no impact on the delay. On the other hand, fulvic and humic acids are soluble in the alkaline pore solution of concrete. Leaching tests are thus performed according to (EN12457-2, 2002) for a 24-hour duration so as to quantify the leaching potential of organic matter in each granular fraction. This test was conducted using a basic solution (NaOH, 1 g/l) in order to replicate the alkaline pore solution of the concrete. The results of leaching tests performed on sediment S6 (Table 12) reveal that the organic matter of the fine fraction ($< 80 \mu\text{m}$) is more soluble than that found in the portion above $80 \mu\text{m}$. Hence, soluble organic matter concentrates in the fine fraction of the sediment, which explains why fine sediments featuring a small organic content still induce a longer delay than an organic-rich sandy sediment. Sieving not only eliminates a significant portion of the organic matter, but it also effectively discharges the soluble organic matter responsible for the delay.

3.2.3. Compressive strength

Among those concretes containing sediment-based sand or coarse aggregates, only one remained in the C30/37 class, while 5 were classified as C25/30 and 4 proved to be C20/25 (Fig. 7). Nevertheless, all mixes containing sand sediments except CS7 fully meet the European Standard requirement (EN12620+A1, 2008). Despite the use of aggregates containing organic matter, the setting time extension was limited, and the 28-day compressive strength was not 20% less than that of the control concrete. In contrast, substituting 30% by vol. of conventional sand by fines sediment triggered a tremendous decrease in compressive strength. The average CF compressive strength at 28 days equaled 19 MPa, i.e. only 50% of that of the control concrete specimen.

The decrease in CG compressive strength may be attributed to the shell content (Fig. 8), as the flat shape of shell elements disturbs the organized granular arrangement formed by conventional aggregates and then increases the total porosity in concrete. Furthermore, the surfaces of these elements create weak adhesion with the mortar, which in turn alters the mechanical properties (Martínez-García et al., 2017; Nguyen et al., 2013a,b). Since G2 is more absorbent and less dense (Table 5), the compressive strength of CG2 is less than that of CG1.

Sediment sand may contain mineral aggregates, crushed shell elements and wood splinters (Fig. 9), hence examining the sediment helps understand its effect on concrete performance. For instance, sandy sediments CS1 and CS7 correspond to the maximum and minimum 28-day compressive strength, respectively. Sediment SS7 visibly features the highest content of lightweight elements, such as wood and slag, while SS1 proves to be the cleanest and contains practically no lightweight elements. Nevertheless, ranking the various mixes in order of ascending compressive strength on the basis of pictures displayed in Fig. 9 proves to be a difficult task. The fresh concrete density is affected by aggregate density, absorption coefficient and the presence of lightweight elements. A low fresh concrete density can thus be attributed to the poor quality of sediment sand substitutes. A linear relationship between density and 28-day compressive strength of the concrete can be observed (Fig. 10).

As reported by (Buth, 1967; Norvell et al., 2007; Rozière et al., 2007; Yalley and Sam, 2018), the main parameters responsible for the low strength of concrete containing fines are: the increase of the fines percentage in sand, and the water/cement ratio. For purposes of our study, fines represent 30% of the sand volume, and the amount of water added to the mix (in order to reproduce the same slump) lies between 38 l/m³ and 108 l/m³, which leaves some uncertainty regarding the actual effective water/cement ratio. These results show that concretes requiring less water (CF2, CF4 and CF11) yield higher strength relative to other fines-based concretes. In addition, the effect of delayed hydration on early-age strength (after 3 days) has been depicted in Fig. 7. For example, concrete incorporating CF6 fine sediments exhibits a longer hydration delay and a lower compressive strength at 3 days, while its compressive strength at 28 days is close to that of other concretes incorporating fine sediments. This finding is consistent with the effects of soluble humic substances, as reported in (Beddaa et al., 2019). In contrast, since sediment sands and sediment gravels do not generate a significant effect on cement hydration, their effect on both early-term and long-term compressive strength remains the same.

3.2.4. Shrinkage

The results of total shrinkage and weight loss are shown in Fig. 11. Strain measurements begin at an age of 1 day for concretes incorporating sand or coarse sediments and 2 days for concretes incorporating fine sediments owing to the extended delay period. Whereas replacing 30% by volume of coarse aggregates by coarse sediments did not affect concrete shrinkage, substituting conventional sand by sands stemming from sediments may or may not induce greater total shrinkage strains. Aggregates reduce the shrinkage strains by restraining shrinkage of the cement paste (Aslam et al., 2016; Wongkeo et al., 2012). The higher the aggregate content, the lower the shrinkage strains. The shrinkage also depends on the mechanical properties of the aggregates, especially their elastic stiffness (Fujiwara, 2008); some aggregates may wind up shrinking. The fact that substituting a volume of conventional aggregates by coarse aggregates stemming from sediments does not affect shrinkage strains suggests that their mechanical properties are comparable. Moreover, the sediment sands triggering the highest shrinkage strains (SC6 and SC7) also feature the greatest absorption, lowest density and induce the least compressive strength at 3 and 28 days. Both contain a significant amount of organic matter. While SC6 is rather fine, sediment SC7 contains a considerable amount of organic matter. The increased shrinkage is likely due to the material being softer, which may be related to the fines, including clays and organic matter contents. Both sediments SC6 and SC7 are indeed rather fine and require more additional water, to a point where the resulting concrete is less dense, weaker and likely softer. Furthermore, shrinkage tends to increase with absorption (Fig. 12). Regarding the fines sediment-based concrete, an explanation for the significant shrinkage is the decrease in total volume of fine aggregates (conventional sand + fine sediments) in the mixture due to the large amount of added water. The shrinkage of concretes containing fine sediments can also be induced by reducing their stiffness, owing to the greater amount of water being added (Rozière et al., 2007). However, these fine sediments likely contain a significant amount of clay, which increases water demand, swells considerably and shrinks significantly at an early age (Buth, 1967). It therefore appears that the water added to produce a satisfactory slump is the relevant factor in determining the magnitude of shrinkage. Fig. 13 reveals that measured shrinkage tends to increase with added water.

4. Conclusion

This work has sought to assess the reuse potential of the Paris Region deposit as aggregates in concrete. Compiling selected information on sediments found in the Seine River watershed has led to a classification of dredged sediments, showing that 30% of these sediments could be viewed as a stable source of clean sandy aggregate. It has also been demonstrated that sieving the sediments to discard their fine fraction is sufficient to recover a valuable substitute to conventional concrete aggregates and sand. Eliminating the fine fraction has indeed efficiently removed the clay and soluble organic matter responsible for extended delays, lower strengths and increased shrinkage strains.

Similarly, coarse aggregates visibly featuring high quantities of shells or porous particles should be discarded; moreover, the amount of water to be added to derive a similar slump serves as a practical index for the quality of the resulting concrete. Greater water demand does signal high amounts of shells, soft porous lightweight particles or fines and clay, along with the correlated occurrence of organic matter. It has been shown that substituting the fine fraction of sediments for sand in concrete clearly extends delays, alters compressive strengths and increases shrinkage strains. Therefore, introducing these sediments into a concrete, as presented in this paper, clearly offsets any economical or environmental benefits. Nevertheless, these fine sediments do constitute a substantial fraction of the deposit, and finding a way to handle these mostly inert and non-hazardous materials, which are presently legally treated as waste, remains a challenge. As regards their reuse in cementitious materials, such particles could be considered as fillers, but it is still necessary to seek low substitution rates, in particular for concretes requiring fines, such as pervious concrete (Zaetang, 2017).

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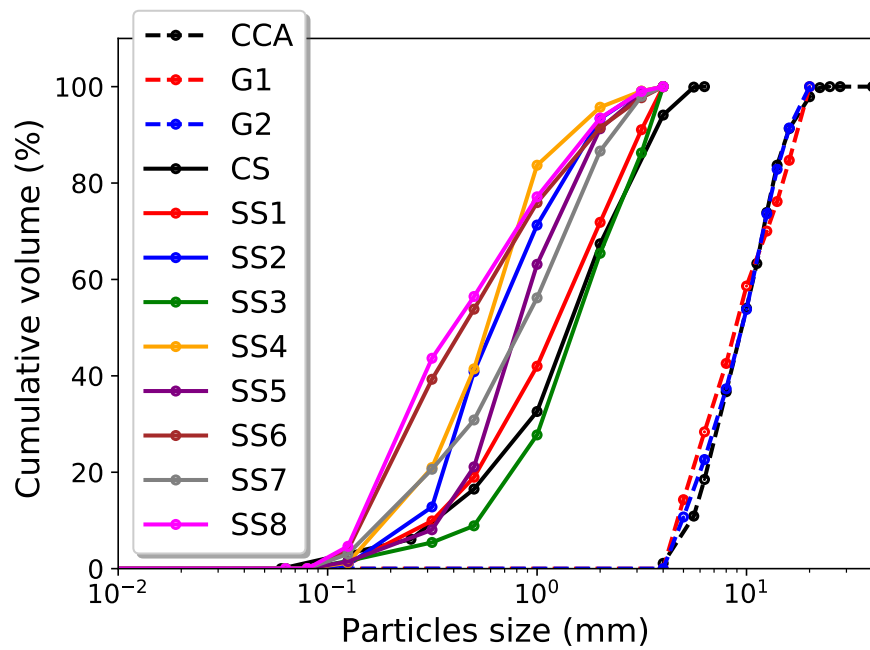


Figure 1: Particle size curves of sediments samples and conventional aggregates



(a) Corbicula.

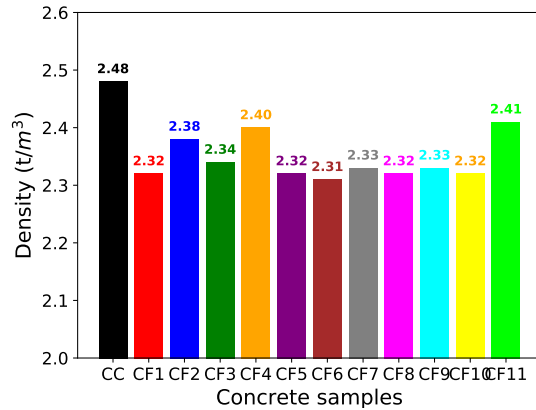
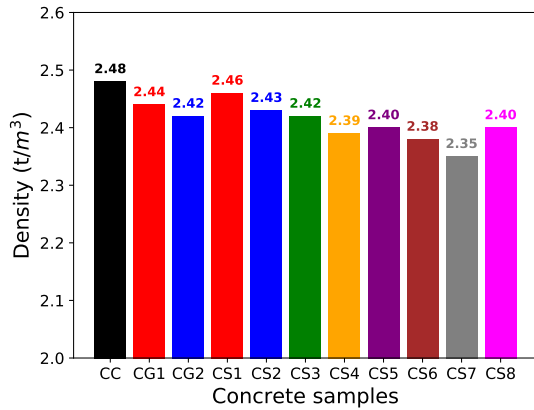


(b) Dreissena.



(c) Viviparus.

Figure 2: Shell families.



(a) Densities of concretes containing sediment gravels (CGs) and concretes containing sediment sand (CSs). (b) Densities of concretes containing sediment fines (CFs).

Figure 3: Density of fresh concrete.

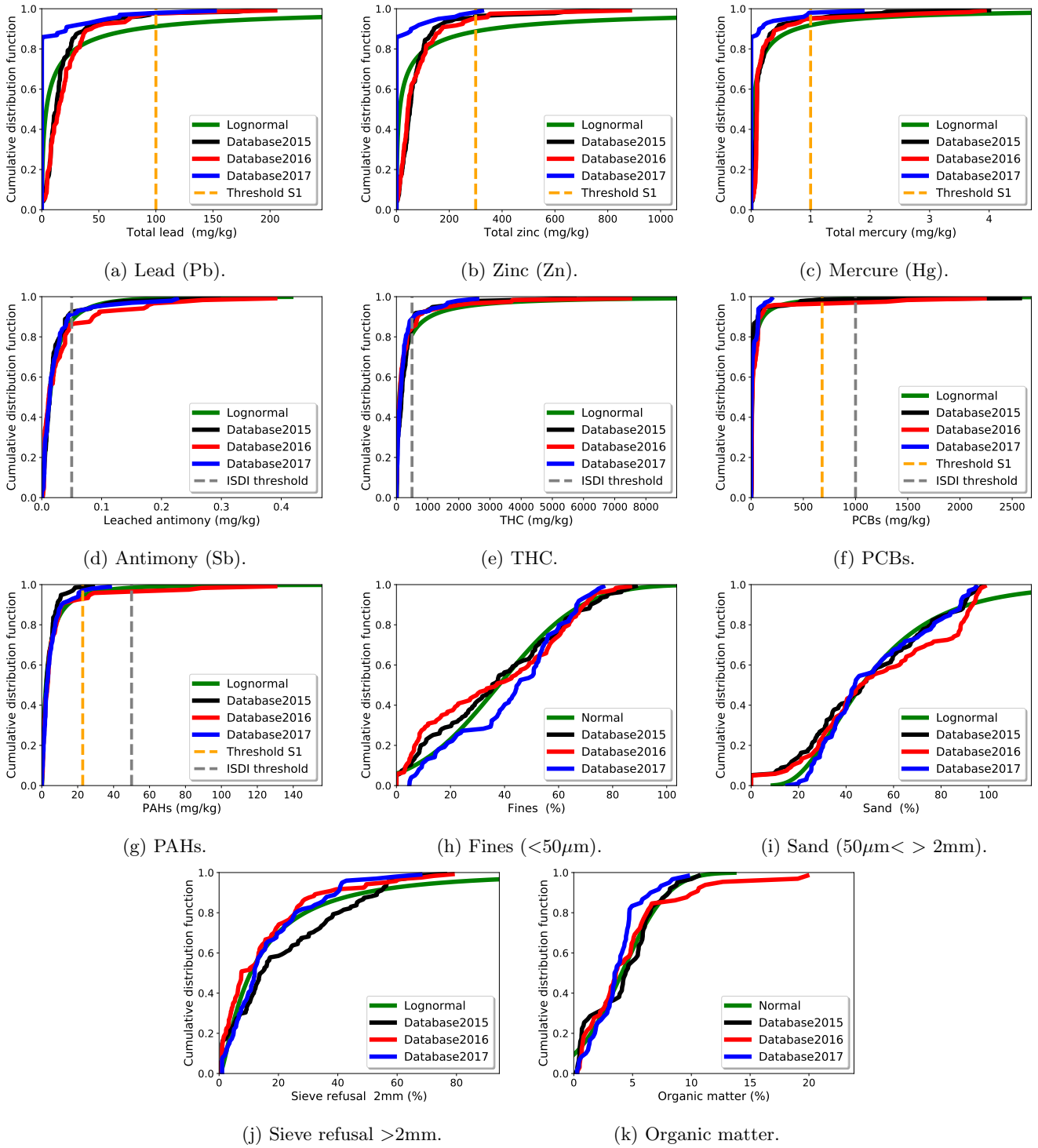


Figure 4: Distribution functions of the different sediment properties.

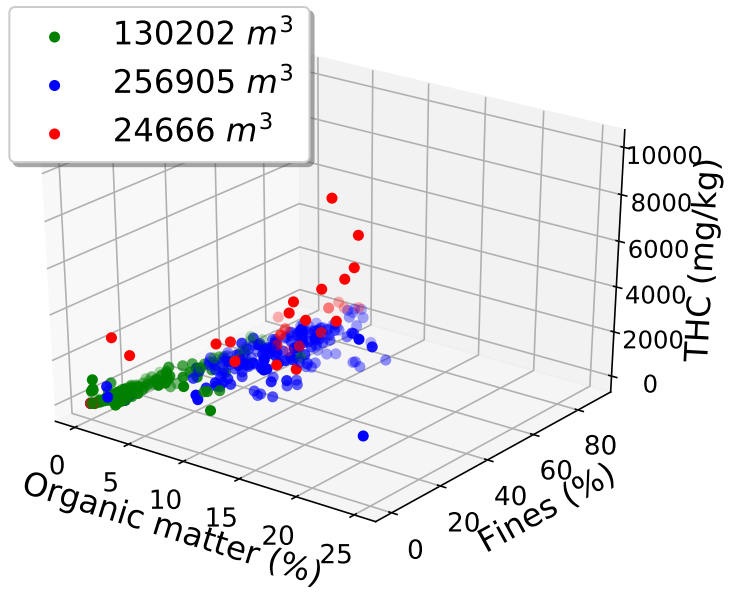
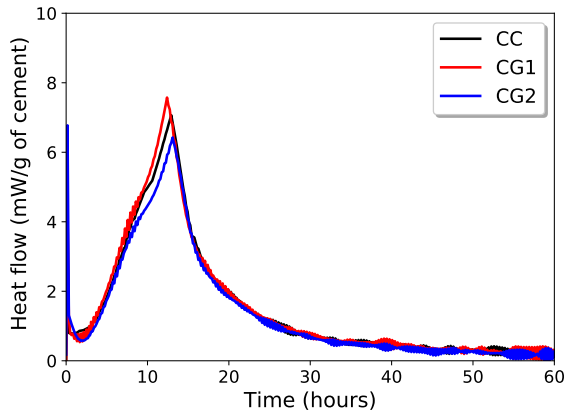
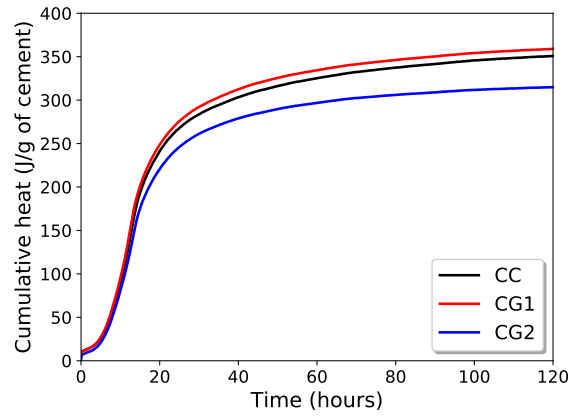


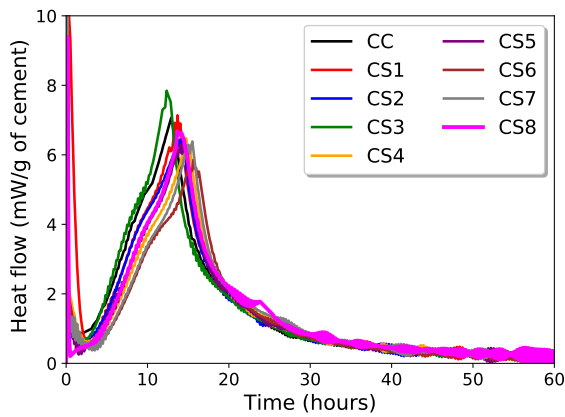
Figure 5: Partitioning samples into three groups according to THC, fines and organic matter contents.



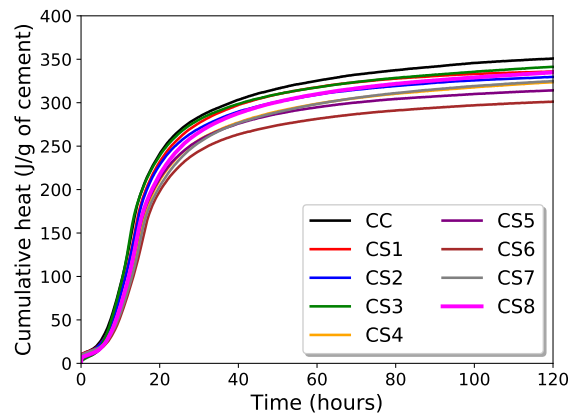
(a) Heat flow for CGs.



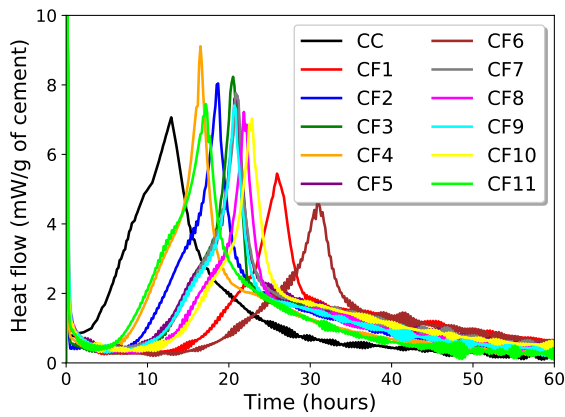
(b) Cumulative heat released for CGs.



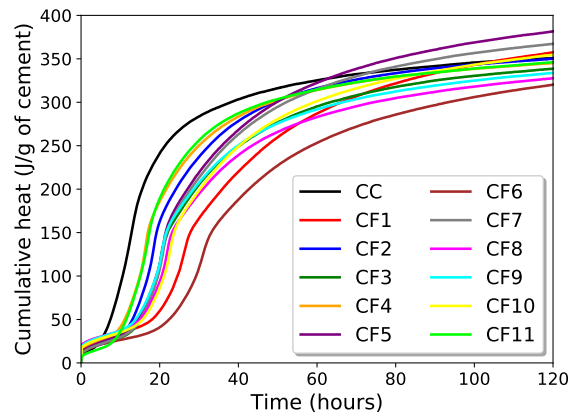
(c) Heat flow for CSs.



(d) Cumulative heat released for CSs.

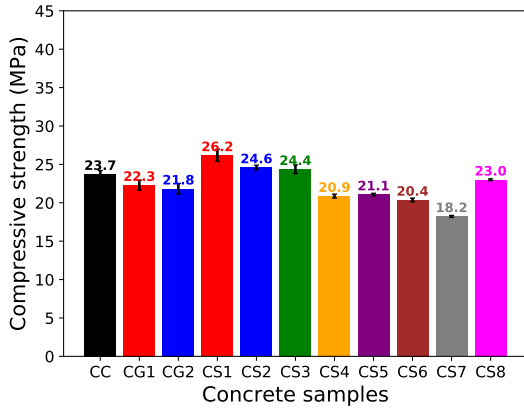


(e) Heat flow for CFs.

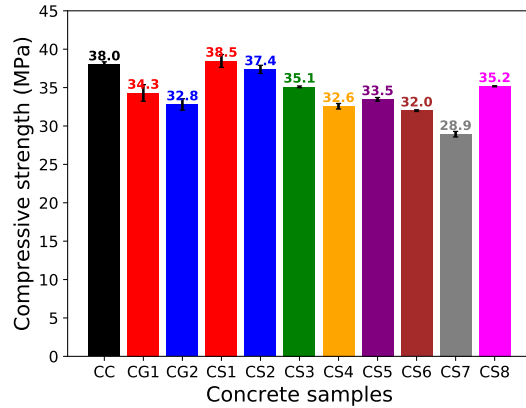


(f) Cumulative heat released for CFs.

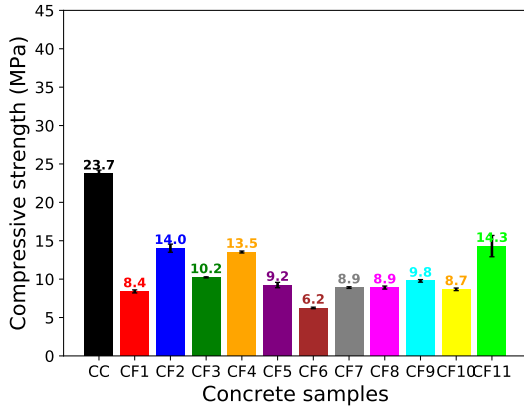
Figure 6: Semi-adiabatic calorimetry tests for different sediment-based concretes.



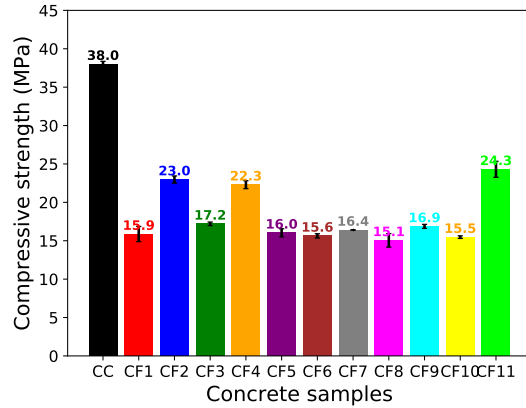
(a) Compressive strength at 3 days for CGs and CSs.



(b) Compressive strength at 28 days for CGs and CSs.



(c) Compressive strength at 3 days for CFs.



(d) Compressive strength at 28 days for CFs.

Figure 7: Compressive strength for all concretes at 3 and 28 days.



(a) CCA.

(b) G1.

(c) G2.

Figure 8: Sediments coarse aggregates, in comparison with conventional one (CCA).

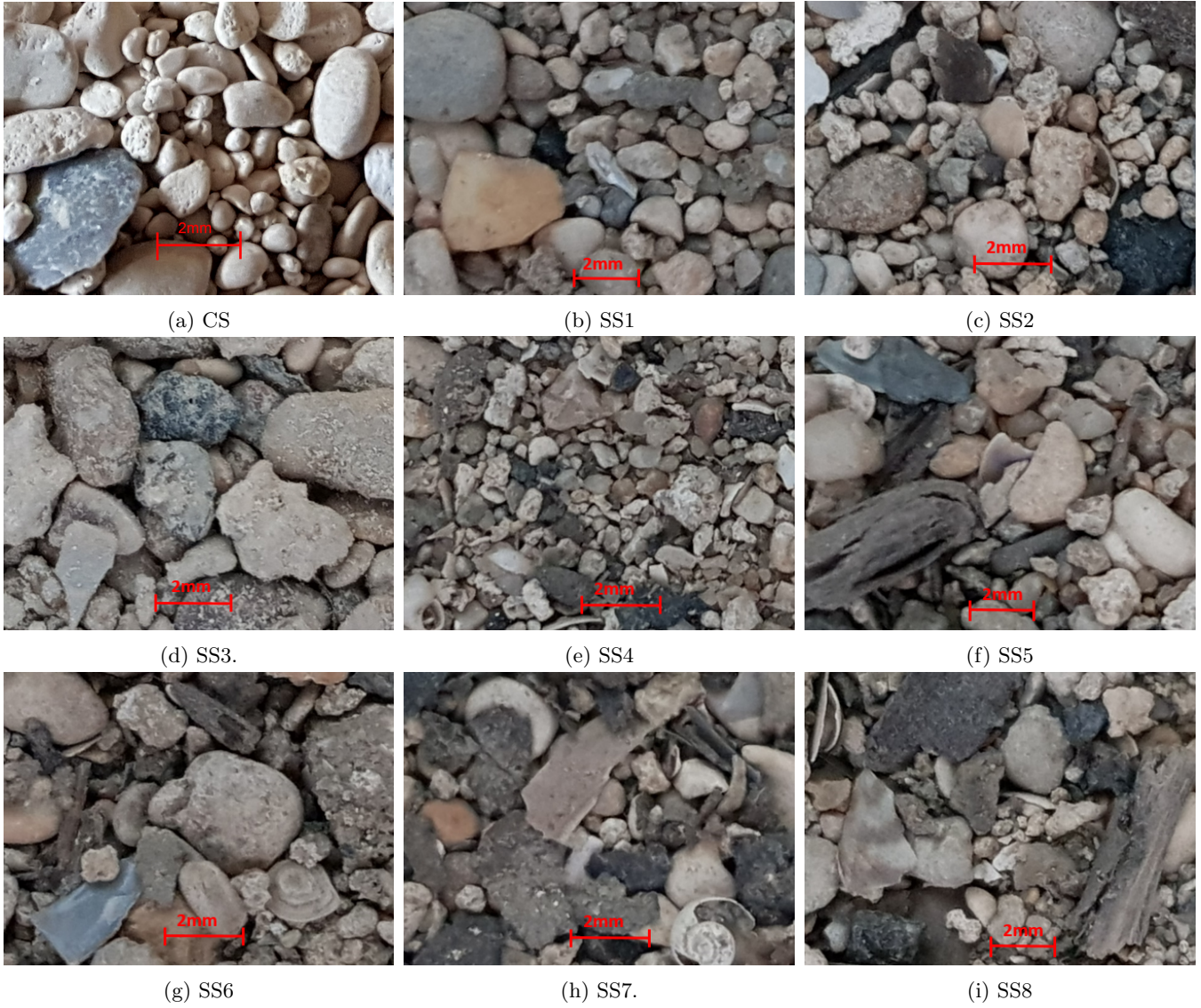


Figure 9: Sediments sands, in comparison with conventional one (CS).

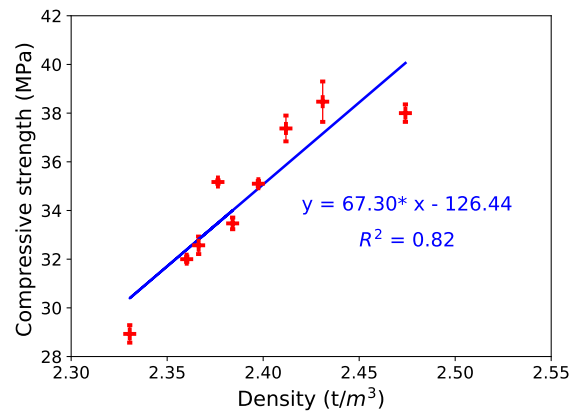
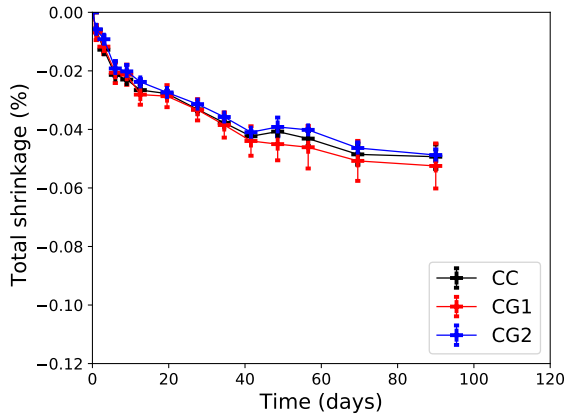
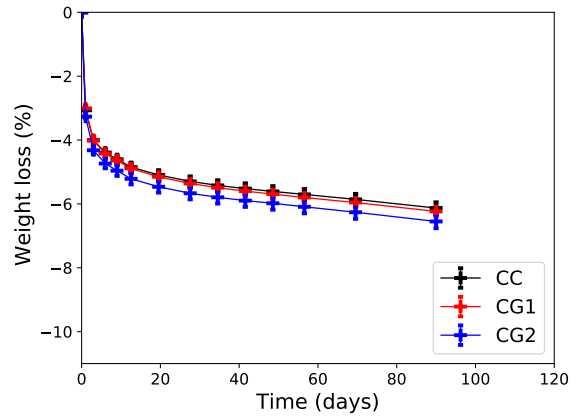


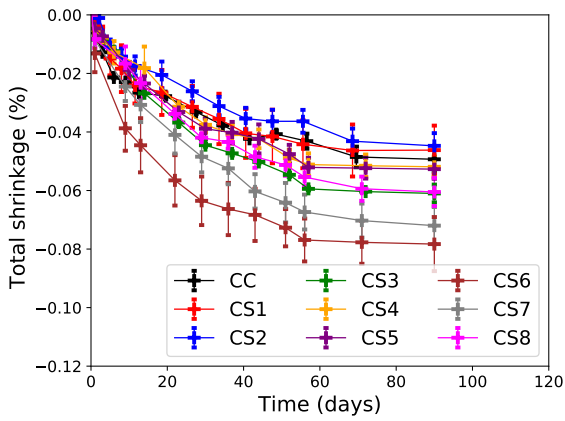
Figure 10: Compressive strength vs. concrete density of CSs.



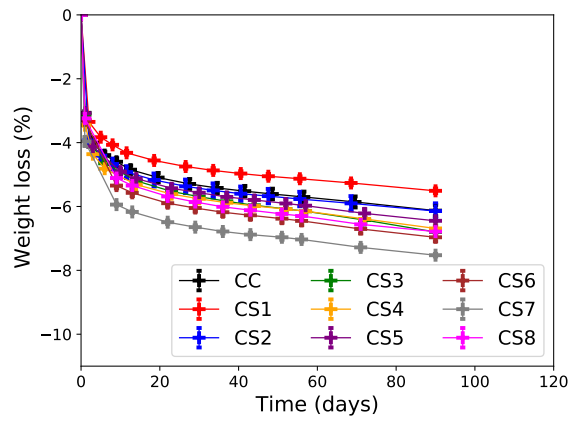
(a) Total shrinkage of CGs vs. time.



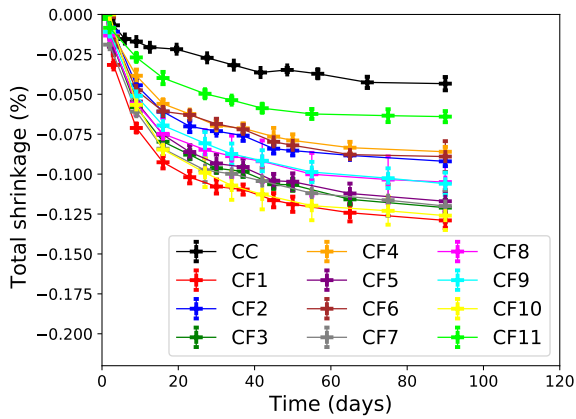
(b) Weight loss of CGs vs. time.



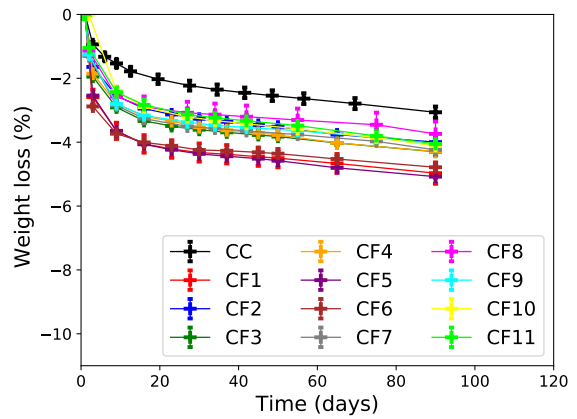
(c) Total shrinkage of CSs vs. time.



(d) Weight loss of CSs vs. time.



(e) Total shrinkage of CFs vs. time.



(f) Weight loss of CFs vs. time.

Figure 11: The variation of total shrinkage vs. time.

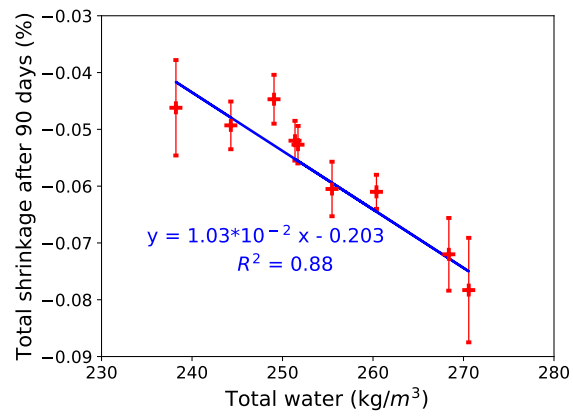


Figure 12: Total shrinkage of CSs at 90 days vs. total water in mixture.

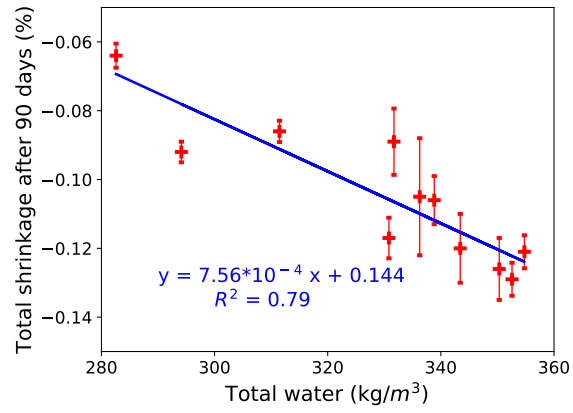


Figure 13: Total shrinkage of CFs at 90 days vs. total water added to the mixture.

Table 1: The characteristic parameters of a sample.

	Parameters	Unit	The ISDI threshold	The S1 Threshold
Heavy metals	Total Lead (Pb)	mg/kg of dray mass	—	100
	Total Zinc (Zn)	mg/kg of dray mass	—	300
	Total Mercury (Hg)	mg/kg of dray mass	—	1
	Leached Antimony (Sb)	mg/kg of dray mass	0.06	—
Pollutants	THC	mg/kg of dray mass	500	—
	Sum of the 7 identified PCBs	μ g/kg of dray mass	1000	680
	Sum of the 16 identified PAHs	mg/kg of dray mass	50	22,800
Particle size	Fines	% dry mass	—	—
	Sand	% dry mass	—	—
	Sieve refusal 2 mm	% dry mass	—	—
Agronomic valorization	Organic matter	% dry mass	—	—

Table 2: The different granular classes in sandy sediments.

Granular fraction	S1	S2	S3	S4	S5	S6	S7	S8
>20 mm	5,3%wt	2,4%wt	17,0%wt	1,2%wt	1,8%wt	3,9%wt	2,0%wt	0,9%wt
Gravels(4/20 mm)	32,6%wt	16,3%wt	33,3%wt	4,9%wt	7,0%wt	27,6%wt	24,4%wt	21,6%wt
Sand(0,08/4 mm)	61,5%wt	80,9%wt	49,1%wt	93,1%wt	90,3%wt	65,9%wt	72,3%wt	75,8%wt
< 80 μ m	0,5%wt	0,3%wt	0,7%wt	0,9%wt	0,9%wt	2,6%wt	1,2%wt	1,7%wt

Table 3: Environmental characteristics of fine sediments.

Parameter	Unit	Method	Samples										
			F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
Lead (Pb)	mg/kg	(EN12457-2, 2002)	13,87	6,41	1,63	1,05	3,44	14,73	15,05	4,48	4,68	10,29	2,57
Zinc (Zn)	mg/kg	(EN12457-2, 2002)	138,53	124,53	121,62	9,16	143,47	154,13	228,17	84,51	128,90	163,57	16,07
Leached Antimony (Sb)	mg/kg	(EN12457-2, 2002)	<0.01	<0.01	1,39E-02	1,72E-02	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	3.10e-02
PCB	mg/kg	(XP-X33-012, 2000)/ (EN15308, 2017)	<0.1	<0.1	<0.1	<0.1	<0.1	0.225	<0.1	0.135	<0.1	<0.1	0.131
Sulphates	mg/kg	(EN-ISO10304-1, 2009)	9.75	18.60	9.55	58.43	19.50	11.50	16.40	12.40	5.25	<5	55.13
Organic matter	%	(XP-P94-047, 1998)	12.66	6.53	9.93	5.39	14.84	12.92	11.91	12.99	12.97	12.88	4.56

Table 4: Environmental characteristics of sandy sediments.

Parameter	Unit	Method	Samples							
			S1	S2	S3	S4	S5	S6	S7	S8
Total Lead (Pb)	mg/kg	(EN12457-2, 2002)	4,537	6,370	2,363	4,675	8,314	1,496	2,477	0,336
Total Zinc (Zn)	mg/kg	(EN12457-2, 2002)	20,470	30,957	22,557	26,937	38,803	12,238	144,063	10,438
Leached Antimony (Sb)	mg/kg	(EN12457-2, 2002)	0	2,574 e-03	0	0	0	0	0	9,455 e-03
PCBs	mg/kg	(XP-X33-012, 2000)/(EN15308, 2017)	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Sulphates	mg/kg	(EN-ISO10304-1, 2009)	37.31	32.73	4.22	70.62	41.82	358.60	5.41	71.36
Organic matter in (<80 μ m)	%	(XP-P94-047, 1998)	11.55	4.48	5.29	8.12	7.53	6.60	5.89	5.45
Organic matter in (80 μ m<>2mm)	%	(XP-P94-047, 1998)	2.01	1.68	1.79	2.55	3.27	3.83	15.05	3.62

Table 5: Absorption coefficient and density of different samples.

Sample	CCA/CS	G1	G2	SS1	SS2	SS3	SS4	SS5	SS6	SS7	SS8
Ab (%)	2.32/4.7	4,1	11,8	3.7	8.5	11.7	8.2	8.1	17.2	16.3	10.0
$\rho(\text{g.cm}^{-3})$: oven-dry density	2.528/2.406	2.308	1.995	2,406	2,219	2,212	2,157	2,220	2,045	2,034	2,141
Sample	F1	F2	F3	F4	F5	F6	F7	F8	F9	F10	F11
Ab (%)	50	25	50	30	45	45	45	45	45	50	20
$\rho(\text{g.cm}^{-3})$	2,196	2,264	2,236	2,413	2,000	2,018	2,255	2,110	2,162	2,155	2,305

Table 6: Flakiness index and shell content in coarse aggregates.

Sample	CCA	G1	G2	
Flakiness index (%)	31%	26%	16%	
Shell content (%)	Corbicula	—	14,64	19,60
	Dreissena	—	8,48	2,50
	Viviparus	—	1,04	2,00
	Total	—	24,16	24,10

Table 7: Chemical composition and physical properties of cement.

Chemical compound	wt.%	Constituents	Characterization of constituents	wt.%
CaO	63.1	Clinker (91.3 wt.%)	C_3S	66
SiO	19		C_2S	11
Al_2O_3	5.4		C_3A	10
Fe_2O_3	2.6		C_4AF	8
K_2O	1		Limestone(3.8 wt.%)	$CaCO_3$
MgO	2	Calcium sulphate(4.9 wt.%)	Gypsum	100.0
Na_2O	0.1		Anhydrite	0.0
SO_3	3.5	Slag	-	-
MnO	0.0	Fly ash	-	-
TiO_2	0.3	Silica fume	-	-
Cl^-	0.02			
S^-	0.02			
Physical characteristics				
Density (g/cm^3)				3.11
Specific surface Blaine (cm^2/g)				3854

Table 8: Mix design.

Sample	Cement (kg)	Conventional sand (kg)	Conventional coarse aggregates (kg)	Sediments (kg)	Effective water (kg)	Total water (kg)	w/c
Control concrete (CC)	335.00	881.10	814.40	0.00	184.25	244.29	0.55
Substitution of 30% by volume of the conventional coarse aggregates by coarse aggregates of sediments (Gs)							
CG1	335.00	881.10	570.08	223.94	184.25	247.80	0.55
CG2	335.00	881.10	570.08	193.57	184.25	261.46	0.55
Substitution of 30% by volume of the conventional sand by sediments sand (SSs)							
CS1	335.00	616.77	814.40	261.72	184.25	238.22	0.55
CS2	335.00	616.77	814.40	241.38	184.25	249.06	0.55
CS3	335.00	616.77	814.40	242.98	184.25	260.38	0.55
CS4	335.00	616.77	814.40	236.94	184.25	251.38	0.55
CS5	335.00	616.77	814.40	243.93	184.25	251.71	0.55
CS6	335.00	616.77	814.40	224.63	184.25	270.58	0.55
CS7	335.00	616.77	814.40	223.50	184.25	268.38	0.55
CS8	335.00	616.77	814.40	235.18	184.25	255.47	0.55
Substitution of 30% by volume of the conventional sand by sediments fines (Fs)							
CF1	335.00	616.77	814.40	241.26	184.25	352.58	0.55
CF2	335.00	616.77	814.40	248.73	184.25	294.13	0.55
CF3	335.00	616.77	814.40	245.65	184.25	354.77	0.55
CF4	335.00	616.77	814.40	265.10	184.25	311.48	0.55
CF5	335.00	616.77	814.40	219.73	184.25	330.82	0.55
CF6	335.00	616.77	814.40	221.70	184.25	331.71	0.55
CF7	335.00	616.77	814.40	247.74	184.25	343.43	0.55
CF8	335.00	616.77	814.40	231.81	184.25	336.26	0.55
CF9	335.00	616.77	814.40	237.52	184.25	338.83	0.55
CF10	335.00	616.77	814.40	236.75	184.25	350.32	0.55
CF11	335.00	616.77	814.40	253.23	184.25	282.59	0.55

Table 9: D-value.

Attribute	Type of distribution	Parameters (mean;std)	D-value	p-value
Total Lead	Log-normal	(1.40 ; 2.37)	0.201	<0.01
Total Zinc	Log-normal	(2.54 ; 2.61)	0.193	<0.01
Leached Antimony	Log-normal	(-4.32 ; 1.11)	0.082	1.67e-2
Total Mercury	Log-normal	(-3.29 ; 2.36)	0.219	<0.01
Sum of the 7 identified PCBs	Log-normal	(2.19 ; 2.00)	0.154	<0.01
Sum of the 16 identified PAHs	Log-normal	(0.87 ; 1.41)	0.076	3.18e-2
Total Hydrocarbons	Log-normal	(4.53 ; 1.91)	0.082	1.67e-2
Fines	Normal	(37.86 ; 24.27)	0.098	<0.01
Sand	Log-normal	(3.84 ; 0.53)	0.079	2.20e-2
Sieve refusal 2 mm	Log-normal	(2.36 ; 1.19)	0.110	<0.01
Organic matter	Normal	(4.08 ; 3.10)	0.105	3.04e-2

Table 10: Correlation matrix.

		Correlation coefficient										
		Lead	Zinc	Leached Antimony	Mercury	PCBs	PAHs	THC	Fines	Sand	Sieve refusal 2mm	Organic matter
e n v i r o n m e n t	Lead	—	0.92	0.55	0.83	0.64	—	0.74	—	—	—	0.38
	Zinc	1.12e-146	—	0.58	0.82	0.65	—	0.78	0.20	—	-0.14	0.41
	Leached Antimony	7.17e-29	1.31e-32	—	0.58	0.45	0.15	0.72	0.17	-0.25	-0.21	0.26
	Mercury	4.30e-90	1.78e-86	8.25e-34	—	0.71	—	0.76	—	—	—	—
	PCBs	9.98e-042	1.16e-44	2.80e-19	3.98e-56	—	0.26	0.72	—	—	—	—
	PAHs	—	—	5.33e-3	—	8.66e-7	—	0.21	—	-0.23	-0.17	0.19
	THC	8.72e-63	4.46e-74	2.53e-57	1.66e-68	3.46e-58	9.20e-5	—	0.19	-0.17	-0.15	0.39
	Fines	—	1.12e-4	1.36e-3	—	—	—	3.43e-4	—	-0.69	-0.40	0.55
	Sand	—	—	2.70e-6	—	—	1.68e-5	1.49e-3	1.11e-50	—	0.32	-0.52
	Sieve refusal 2 mm	—	9.98e-3	8.18e-5	—	—	1.19e-3	6.35e-3	2.29e-15	5.57e-10	—	-0.41
	Organic matter	6.97e-8	4.24e-9	2.64e-4	—	—	9.39e-3	3.25e-8	3.49e-16	2.37e-14	3.98e-9	—

Table 11: Total heat released, maximal flow and its time of appearance.

Sample	CC	CG1	CG2	CS1	CS2	CS3	CS4	CS5	CS6	CS7	CS8
Cumulative Heat after 5 days (J/g of cement)	350.93	359.15	314.94	336.03	329.67	341.27	323.65	314.25	301.25	324.91	335.04
Maximum flow (mW/g)	7.07	7.57	6.43	7.14	6.44	7.85	6.48	6.29	5.86	6.29	6.63
Time of appearance (hours)	12.92	12.40	13.09	13.69	14.01	12.34	14.75	14.05	15.65	15.01	14.17
Sample	CF1	CF2	CF3	CF4	CF5	CF6	CF7	CF8	CF9	CF10	CF11
Cumulative Heat after 5 days (J/g of cement)	357.37	350.08	338.67	345.08	381.62	320.31	367.28	327.64	333.83	354.69	346.03
Maximum flow (mW/g)	5.45	8.04	8.23	9.11	7.70	4.61	7.77	7.22	7.41	7.03	7.45
Time of appearance (hours)	25.92	18.68	20.52	16.52	21.01	31.01	20.85	21.84	20.68	22.84	17.17

Table 12: The organic matter (OM) content before and after a leaching test on the sediment S6.

	Total OM (%)	Total OM after leaching test (%)	The percentage of leached OM (%)
<80 μ m	6.6	5.43	17.7
80 μ m <> 2mm	3.83	3.45	9.92