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Characterizing Harbor Dredged Sediment for Sustainable Reuse as Construction Material

Meryem Bortali [1,*], Mohamed Rabouli [2], Madiha Yessari [1] and Abdelowahed Hajjaji [1]

[1] National School of Applied Sciences of El Jadida, Chouaib Doukkali University, Aazzemour Road, National N°1, El Haouzia, El Jadida 24002, Morocco
[2] National School of Applied Sciences of Kenitra, Ibn Tofail University, University Avenue, Kenitra 14000, Morocco
* Correspondence: bortali.m@ucd.ac.ma

Abstract: An unprecedented rate of construction has profoundly increased the risk of scarcity of natural resources and threatened ecosystem sustainability. To establish an effective sustainable development policy, it is imperative to promote the use of responsible production channels, including waste recycling. Reuse of harbor dredged sediment is commonly investigated as a valuable alternative to non-renewable natural resources needed for construction. Sediment characterization is decisive in the valorization process, aiming to identify potential recycling paths. Existing research efforts, however, have rarely investigated case studies in developing countries. Moreover, they have tended to focus on the technical aspects, ignoring economic feasibility, which carries important implications. This paper fills this gap first by meticulously selecting laboratory tests for characterization within the means available in developing countries and second by conducting a cost-benefit analysis. The port of Safi, Morocco, was chosen for the implementation of the adopted approach. Results showed that dredged sediment is a sand readily reusable as a construction aggregate. Several applications are possible, the most interesting one being concrete works, as a substitute for conventional sand. While treatment by washing and dehydrating proved necessary, cost-benefit analysis confirmed the profitability of recycling. Hence, beneficial reuse of dredged sediment as construction material is technically and economically feasible.

Keywords: reuse; sustainability; dredged sediment; construction material; characterization

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1. Introduction

Construction projects generate significant quantities of solid waste [1–4], which presents many difficulties for sustainable development and circular economy [2]. New construction projects have promoted economic growth in developing countries [5], but simultaneously generated new waste management challenges to overcome [6,7]. Santoso et al. [7], for example, investigated waste management as a critical factor affecting the performance of large construction projects in developing countries. According to McDermot et al. [8], a lack of an efficient material management is one of the most common failure factors that decrease the performance of infrastructure projects in developing countries. Kassem et al. [9] argued that construction waste is one of the most important risk factors in oil and gas construction projects in developing countries. Other studies considered that the inclusion of material management, among other criteria, guarantees the success of public-private partnership infrastructure projects in developing countries [10]. This situation has put construction industries under pressure to consider appropriate methods for managing construction waste [11–13]. Recycling represents an efficient way to counter the risk of construction waste [4,14–16]. Within this context, large amounts of dredged sediment are produced as part of the construction of new ports, marine structures or waterways [17]. Marine sediment can be generated by other activities such as the deepening of access channels and port basins, and regular dredging operations to maintain adequate depths [18–22].

The enormous quantities of sediment are explained by the presence of anthropogenic activities occurring naturally [21]. Considered as waste [23], dredged sediment is often disposed of into the sea [24], causing adverse consequences on the aquatic environment and human well-being [17,25–30]. Given the increasing legal requirements regarding sediment management, conventional methods or the "no-action" option are no longer viable for economic, environmental and social plans [31–33]. Dredged sediment management is therefore a challenge and an opportunity for port authorities [28,34,35] to apply circular economy principles by considering sediment as a sustainable resource rather than hazardous waste [36–38].

In addition, construction projects have accelerated at an unprecedented rate due to rapid urbanization [39]. Requiring large volumes of raw materials [40,41], the construction industry is disadvantaged by the scarcity of natural resources [42,43]. As future construction projects are planned to expand [44–46], it is critical to adopt development plans that promote the use of responsible production channels, including waste materials recycling [47–50]. From this perspective, sustainable reuse of harbor dredged sediment may provide a valuable alternative to the overexploitation of the non-renewable natural resources needed for construction [51,52]. Dredging operations, performed periodically in order to guarantee adequate navigation levels and ports safety [28,53–55], generate more than 1 billion cubic meters of sediment per year worldwide [56]. To this effect, many studies have examined the feasibility of reusing dredged sediment as construction material [57,58]. Research into this field has focused on recycling dredged sediment as a secondary raw material in different applications as a way to preserve non-renewable resources and reduce the environmental impacts of off-site marine disposal [53]. Although the material obtained from dredged sediment is non-renewable, it has several characteristics and advantages in terms of sustainability [59]. Firstly, the quantities generated by dredging operations are immense and present a significant resource to fill the need for construction materials [60]. Secondly, dredged sediment is the result of a natural phenomenon called sedimentation; it is a continuous and permanent process resulting from the transport of particles and their ultimate accumulation in the marine basin to form a deposit [54,55,61]. This is confirmed by the rising statistics of the quantities dredged per year. It should be noted that recent years have recorded, at the world level, an amplification of the phenomenon of sedimentation and an increase of its speed due to erosion and an increase in anthropic contributions [62]. Therefore, unlike the case of quarries and natural deposits, the reuse of dredged sediment in the construction sector does not face constraints related to the rational management of non-renewable resources.

As the bridge which links dredging operations and extracted products management, the beneficial reuse of dredged sediment as construction material represents a concrete application of efficient waste management [63]. It allows for both a sustainable dredging disposal mechanism and the promotion of a waste-to-wealth approach [56,64–68]. A number of studies have identified paths to valorize dredged material in the construction industry [59,69,70]. Dredged sediment can be used as an alternative source of conventional aggregate used for the manufacture of concrete or mortar [24,60,71–74] by acting as a substitute for sand. It can also partially replace raw materials for cement production [75–77]; this often requires adequate treatment before use. More studies have focused on the reuse of dredged sediment as foundation or base layers in road engineering [34,78–83]. Some researchers have investigated the feasibility of recycling dredged sediment in brick production [51,84–88], artificial aggregate [53,87,88] and urban landscaping works [89,90]. As a result, the technical feasibility of recycling dredged sediment in the construction industry has been confirmed. However, most of these studies do not examine real applications of recycled sediment. Few researchers have attempted to realize projects based on these materials. Amar [90,91], for example, worked on three in-site projects at the seaport of Dunkerque; the first was the replacement of a 600-m-long road (Freycinet 12) of degraded pavement using base layers from non-immersible sediment. The second project consisted of valorizing dredged sediment into maritime concrete blocks that are used to stabilize the jetty at the West Foreport to control the agitation of water bodies. The third project served to enhance sediment into a landscaped eco-model; this project consisted of the implementation of landscaping eco-models made of sediments from 5 to 7 m high and covered with 0.25 m of topsoil to ensure the stability of the structure. In addition, dredged sediment has been used in some countries in major infrastructure projects, such us Palm Island in Dubai, Rotterdam harbor, the National Theatre in London and the artificial island of Chek Lap Kok where the Hong Kong airport is located [72,92,93]. The success of these projects confirms and verifies the economic and technical validity of reusing dredged sediment in civil engineering [94].

Research has proven the potential of recycling dredged sediment in many applications related to the construction industry [36,56,94]. However, market demand appears to be lagging behind encouraging study results; the real beneficial reuse of dredged sediment is still very limited [95,96]. From a technical point of view, the identification of the appropriate path to valorize dredged sediment as construction material should be based on the study of its properties [56]. It requires a case-by-case basis in order to determine the required characteristics of sediment extracted from the study site [27]. Characterizing the dredged sediment is therefore considered as an essential phase towards identifying the possible recycling paths of sediment [23,35]. This constitutes a primordial and decisive step in the valorization process [97,98]. Research efforts in this context were often conducted from the perspective of providing a study of all parameters related to dredged sediment characterization, including on-site analysis and laboratory tests [99]. Researchers have opted for physical, microscopic, chemical, mineralogical, environmental, mechanical and geotechnical characterizations [72,85,100–103]. With a growing interest in sustainable development issues, characterization tests of dredged sediments are often imposed by regulatory frameworks in order to determine their best destination [27,104]. However, prior research has focused mostly on case studies in developed countries, and there have been limited efforts to explore how these approaches can be implemented in developing countries [101]. Developed and developing countries have quite divergent concerns; while in developing countries the pursuit of more cost-effective development opportunities frequently overrides environmental considerations and concerns, developed countries are often economically strong and able to place a higher emphasis on sustainable development and environmental issues [29,98,105–108]. Such an approach to complete and full characterization is not applicable in developing countries; in addition to the legal gap in which dredged sediment management does not mandate any type of characterization [23,56,109], it requires an investment in terms of cost, time and advanced techniques for conducting all types of laboratory tests. The number and complexity of characterization tests are an obstacle to the valorization process in developing countries. Hence, optimizing and justifying the choice of laboratory tests carried out to characterize dredged sediment is instrumental for recycling it as construction material in developing countries.

On the other hand, previous studies have focused only on the technical feasibility of reusing dredged sediment in civil engineering [110]. This reuse process combines an environmental issue with an economic advantage [56]. Indeed, the final objective of this process is to no longer to store or dump the dredged sediment, but rather to use it as commercial material. Beneficial reuse of dredged material may become more cost-effective in the future due to the scarcity of natural resources and the possible increase of their price [56]. Accordingly, estimating the necessary costs to obtain construction material from dredged sediment is important in order to compare it with the cost of purchasing a similar conventional material [17,28,111–113].

In this study, only the characteristics necessary for the evaluation of the feasibility of dredged sediment reuse as construction material have been determined, through an experimental study completed by a statistical approach. The use of each laboratory test was justified. Prior to the characterization study, some essential criteria needed be taken into consideration. First was the choice of the study site, which depended on the level of silting in the basins and channels of the selected port, its size and its geographical position, as well as the nature and volume of traffic transiting through this port. Second was the choice of the sampling method that would provide the best information value of studied sediment [91]. Furthermore, collection in the field and storage conditions of the sediment samples were decisive criteria for the quality of obtained results [114].

With the longest coastline in Africa (3500 km), Morocco has 43 ports, including 14 ports open to foreign trade, 22 fishing ports and 7 marinas. More than 3.4 million cubic meters of sediment is dredged annually to fight against the silting up of Moroccan ports [115]. Among others, Safi harbor is experiencing heavy silting [116,117], which requires the regular dredging of 250,000 cubic meters per year from the access channel [118]. In order to determine the properties of sediment extracted from the port of Safi, the essential parameters for the physical, geotechnical, chemical and mineralogical characterization have been analyzed. The characteristics related to particle size analysis, water content, methylene blue value, sand equivalent, apparent density, absolute density, chloride content, sulfate content and mineral composition were obtained through an experimental study and a statistical approach. The need for each test was justified. The outputs were used to classify dredged sediment based on the European standards in force. Recommendations were then put forward to determine the possible recycling paths of dredged sediment in the construction industry, considering the cost of obtaining the final product in comparison with the cost of conventional material. This study provides the necessary outcome that offers the means for decision making with respect to the sustainable reuse of dredged sediment.

2. Materials and Methods

2.1. Study Area

Safi harbor, located in the center of the Atlantic coast of Morocco (32.312642, −9.252548), has a vast territory that covers a land area of approximately 66 hectares and water surfaces of 43 hectares. It is built at the bottom of a bay dominated by high, wide-open cliffs that offer shelter to ships against winds and storms [116–119]. The port of Safi is one of the oldest ports in Morocco. It experienced a flourishing of activity during the nineteenth and twentieth centuries [119]. The main port activities are trade and fishing, with annual traffic exceeding 6.5 million tons, which represents 7% of the national traffic. Two jetties with a total length of 2.2 km protect Safi harbor. Its infrastructures are organized in three basins: Basin I (three quays dedicated to fishing activity), Basin II (four quays handling the traffic of phosphates, fertilizers, ores and cereals) and Basin III (two quays handling the traffic of phosphoric acid and sulfur). It also includes a shipyard for fishing boats. Safi harbor is experiencing strong silting; the average volume of sediment movement on the Atlantic coast is about 250,000 m^3/year, from the erosion of cliffs (Cape Ghir-Arhesdis) and inputs from the open sea and wadis. The amount of marine sediment dredged annually is estimated at 250,000 m^3 [117,118]. Figure 1 represents the study area location.

2.2. Data Collection

In order to obtain representative samples that reflect the real characteristics of marine sediment in the port of Safi, 6 points were selected from its different areas: one point from the commercial basin (P1), one point from the ore basin (P3), one point adjacent to both basins (P2), one point in the harbor pass (P4), one point in the access channel (P5) and one point next to the main jetty's breakwater (P6). A diver using a boat collected the samples in November 2021. They were placed in insulated bags of 20 liters each (two bags per sampling point), with the name of the sample and the date of collection indicated on each bag. These bags were kept in an opaque room at 4 °C during the tests [114]. Figure 2 shows the locations and the coordinates of sample collection points.

Figure 1. Location of Safi harbor, Morocco.

Code	Coordinates	
	Latitude	Longitude
P1	9°24′76.9″W	32°30′75.8″N
P2	9°25′03.7″W	32°30′94.4″N
P3	9°24′97.1″W	32°31′12.0″N
P4	9°25′28.9″W	32°31′20.7″N
P5	9°25′36.4″W	32°31′32.0″N
P6	9°25′54.2″W	32°31′37.1″N
Safi Harbor, Safi, Morocco		

Figure 2. Locations and coordinates of sampling points.

Collection of two different bags per sampling point was carried out to identify the characteristics at each point. The characterization by zone or by basin is essential for the commercialization of the sand thereafter. As for quarries and natural deposits, the characteristics of the dredged sand must be communicated to the final customer beforehand. This involves identifying the properties of the dredged sand from each part of the basin.

2.3. Methods

2.3.1. Selection and Optimization of Tests

The study of sedimentary characteristics has shown that sediment from the region of Safi is sandy [120,121]. Based on the assumption that sediment dredged from Safi harbor is of a similar nature, and in order to study the possibility of its reuse as an aggregate for concrete, the usual tests carried out for the determination of conventional sand properties have been selected.

(1) Geotechnical characterization

Grain size analysis consists of deriving the distribution of the different grains constituting the dredged sediments, according to their weight and size. Based on the range of the particle sizes, sediment can be classified in generic categories. Granulometric and statistical parameters have been calculated to investigate the geotechnical properties of dredged sediment.

(2) Physical characterization

A water content test (w) makes it possible to determine the quantity of water contained in dredged sediment. A sand equivalent test (SE) makes it possible to highlight the degree of cleanliness of the sand from the proportion of harmful fine dust of essentially clay, vegetable or organic origin. Tests of apparent density ($\rho_{apparent}$) and absolute density ($\rho_{absolute}$) make it possible to calculate the porosity of studied sediment. A methylene blue value test (MBV) is used to assess the specific exchange surface of clay particles contained in sediments; the value obtained expresses the quality and activity of the clay fraction (<2 µm) of the 0/5 mm fraction included in the sediment.

(3) Chemical characterization

Testing for sulfate and chloride content in dredged sediment ensures that structures are not affected by these ions. Chloride and sulfate ions are considered secondary contaminants. Chloride, like other salt and acid ions, promotes steel corrosion [122]. Over time, sulfate can attack concrete structures [123].

(4) Mineralogical characterization

Mineral composition is a fundamental characteristic that affects soil properties and functions through physical, chemical and biological interactions with other aggregates [124].

2.3.2. Sediment Characterization Tests

A sediment preparation step was performed before starting laboratory tests to characterize dredged sediment. Each sample was divided into parts required for the different tests. For the water content test and particle size analysis, the preparation step consisted of quartering and then washing the collected samples with distilled water and finally drying them in an oven at 105 °C for 24 h. The water content was determined on duplicate test portions. Particle size analysis by sieving the samples was performed on 200 g of washed and dried sediment. For each sample, a column composed of 9 nested sieves of the AFNOR series was used. The sample was poured in and the sieve column was agitated. Then, each sieve was manually moved in descending order of the sieve opening diameter. The refuse collected on each sieve was weighed. Obtained masses were calculated and expressed as percentages of the initial mass and as cumulative percentages.

Collected samples were also tested for sand equivalent, apparent density, absolute density, methylene blue value, chloride content, sulfate content and mineral composition. For each sample bag, the tests carried out were repeated three times to confirm the results obtained. Thus a total of 6 tests were performed per location. Table 1 summarizes the procedures and standards related to each test.

Table 1. Tests carried out on the dredged sediments of Safi harbor.

Test	Procedure	Standard
Water content (w)	Heating at 105 °C until constant mass is obtained, then determination of the mass loss	EN 1097-5 [125]
Particle size analysis	Washing, sieving and weighing of the refusals of a series of 9 sieves	EN 933-1 [126]
Sand Equivalent (SE)	Filling and stirring of graduated cylinders, then washing and measuring the heights after rest	EN 933-8 [127]
Apparent density ($\rho_{apparent}$)	Immersion in water for 24 h and weighing of the different masses of containers and aggregates before and after steaming	EN 1097-6 [128]
Absolute density ($\rho_{absolute}$)	Filling of the pycnometer, placement in a water bath at 25 °C and weighing of the different masses of the empty and filled pycnometer	EN 1097-7 [129]
Methylene blue value (MBV)	Preparation of the suspension and determination of the amount of dye absorbed	EN 933-9 [130]
Chloride content	Precipitation of chlorides in aqueous silver nitrate solution, then determination of the excess of silver ions by a titrated solution of potassium thiocyanate. End of determination by using a colored indicator	EN 1744-1 [131]
Sulfate content	Extraction of water-soluble sulfate ions, then determination by gravimetry	EN 1744-1 [131]
Mineral composition	Diffraction by X-ray technique to identify the minerals in sediment composition	EN ISO 14688-1 [132]

2.3.3. Granulometric Parameters

Raw results from particle size analyses were plotted and calculated to determine the sediment characteristics. Many techniques can be used to represent the obtained results in index or graphical form [133]. The most common graphical representations are cumulative and differential distribution curves. We were interested in the first type of graphical representation, opting for a logarithmic scale on the abscissa to represent the diameter of the mesh openings of the sieves used, and an arithmetic scale on the ordinate to show the cumulative percentages of refusals. Granulometric parameters were calculated according to the standards EN 12620 [134] and NF P 18-545 [135].

(1) Granular class

The granular class, d/D, makes it possible to obtain the general characteristics of the granularity of studied sediments, with d being the minimum diameter of the grains and D being the maximum diameter.

(2) Fineness modulus

Fineness modulus, F_M, represents the average particle size in the sediment by an index number. The larger the sediment size, the higher the fineness modulus. It is calculated as shown in Equation (1).

$$F_M = \frac{\sum cumulative\ refusals\ in\ \%\ of\ sieves\ \{0.125 - 0.25 - 0.5 - 1 - 2 - 4\}}{100} \quad (1)$$

(3) Uniformity coefficient

Coefficient of uniformity, C_u, allows us to determine the level of uniformity of the sediment grain size by indicating the irregularity of the distribution of this size. It is calculated according to the formula of Equation (2), with D_{60} and D_{10} being grain diameters (in mm) corresponding to 60% and 10%, respectively, passing by weight.

$$C_u = \frac{D_{60}}{D_{10}} \quad (2)$$

(4) Curvature coefficient

Curvature coefficient, C_C, defines the relative variation of the curve slope. Equation (3) shows the formula to calculate the curvature coefficient, with D_{30} being grain diameter (in mm) corresponding to 30% passing by weight.

$$C_c = \frac{{D_{30}}^2}{D_{10} \times D_{60}} \tag{3}$$

2.3.4. Statistical Parameters

Based on the cumulative curve, the parameters and indices below were deduced and calculated. We were mainly interested in Trask and Folk and Ward indices [133]. Calculations of statistical parameters were conducted in unit φ [133,136], with $x_\varphi = -\log_2 x$ (where x is the dimension in mm).

(1) Position parameters

Position parameters give an estimate of the coarseness of the sediment. Quantile Q_x is the point corresponding to the grains hypothetical size, to which corresponds a cumulative percentage by weight of the sediment, x%. We were interested in the values of the median Q_{50}, the percentiles Q_5 and Q_{95}, the fractiles Q_{16} and Q_{84} and the quartiles Q_{25} and Q_{75}.

(2) Dispersion parameters

Dispersion parameters are indicators of the grading quality of a sediment based on the slope of the cumulative curve. The indices holding our interest were the sorting-index S_0 of Trask, the dispersion index of Folk and Ward (also called standard deviation) σ and the mean grain M_Z of Folk and Ward. They were calculated respectively as shown in Equations (4)–(6). Mean grain results calculated in unit φ were converted to mm to obtain physical meaning.

$$S_0 = \sqrt{\frac{Q_{25}}{Q_{75}}} \tag{4}$$

$$\sigma = \frac{Q_{84\varphi} - Q_{16\varphi}}{4} + \frac{Q_{95\varphi} - Q_{5\varphi}}{6.6} \tag{5}$$

$$M_z = \frac{Q_{16\varphi} + Q_{50\varphi} + Q_{84\varphi}}{3} \tag{6}$$

(3) Asymmetry parameters

The asymmetry indices determine the shape of the particle distribution on either side of the median (they measure the deviation of the particle size curve towards fine or coarse particles compared to the normal distribution). The indices used are the asymmetry index of Trask SK and the skewness of Folk and Ward SK_σ, calculated according to the formulas of Equations (7) and (8), respectively.

$$SK = \frac{Q_{25} \times Q_{75}}{{Q_{50}}^2} \tag{7}$$

$$SK_\sigma = \frac{Q_{84\varphi} + Q_{16\varphi} - 2 \times Q_{50\varphi}}{2 \times (Q_{84\varphi} - Q_{16\varphi})} + \frac{Q_{95\varphi} + Q_{5\varphi} - 2 \times Q_{50\varphi}}{2 \times (Q_{95\varphi} - Q_{5\varphi})} \tag{8}$$

(4) Acuity parameters

The acuity parameters determine how flattened the grain size curve is; they are indicators of the smoothness or the width of the peak of the curve. The index used is the kurtosis of Folk and Ward K_σ. It is calculated as shown in Equation (9).

$$K_\sigma = \frac{Q_{95\varphi} - Q_{5\varphi}}{2 \times (Q_{75\varphi} - Q_{25\varphi})} \tag{9}$$

For all statistical parameters, it is specified that the interpretations of the results were carried out according to the classification categories fixed by the formula authors.

2.3.5. Cost-Benefit Analysis

Cost-benefit analysis allowed us to study the economic feasibility of reusing the dredged sediment as construction material. A price study was performed to estimate all costs related to the production of the final material. The cost of recycling was compared with the cost of purchasing a similar conventional material.

3. Results

The results presented in this research are the averages of the outcomes of the six tests performed by sample point; first, the average of each of the three tests performed per sample was calculated, giving two values per sampling point, and then the result of averaging the two values obtained was taken into consideration.

3.1. Geotechnical Characterization

Grain size analysis provided the particle size distribution of dredged sediment. Table 2 shows the cumulative percentages of material passing through each of the used sieves. In general, dredged sediment is composed of grains with diameters between 0.063 mm and 3.15 mm. On average, 90% of dredged sediment grain diameters are between 0.315 mm and 1.25 mm. Samples P1, P2, P3 and P4 contained more fine particles than samples P5 and P6. The first four samples were composed of 86% grains with diameters ranging from 0.16 mm to 1.25 mm. The two other samples were composed of 82% grains with diameters between 0.315 mm and 1.25 mm. According to the triangle of textures [137], sediment dredged from the port of Safi is mainly sandy.

Table 2. Particle size distribution of sediment dredged from Safi harbor.

	Sample	P1	P2	P3	P4	P5	P6	Min	Max	Mean	Median
Passing (%)	0.063 mm	10.3	3.1	3.8	2.9	1.1	1	1	10.3	3.70	3
	0.08 mm	11.7	3.9	4.7	3.3	1.3	1.2	1.2	11.7	4.35	3.60
	0.16 mm	19	10	11	10	3	2	2	19	9.17	10
	0.315 mm	70	71	67	75	20	16	16	75	53.17	68.50
	0.63 mm	97	97	96	98	96	97	96	98	96.83	97
	1.25 mm	98	99	98	99	100	100	98	100	99.00	99
	2 mm	99	99	99	100	100	-	99	100	99.40	99
	2.5 mm	99	100	99	100	-	-	99	100	99.50	99.50
	3.15 mm	100	100	100	100	-	-	100	100	100	100

Figure 3 represents the cumulative percentage distributions of refusals. The distributions of samples P2, P3 and P4 have the same shape. Sample P1 distribution differs on the finest particles diameters. The distributions of samples P5 and P6 have the same shape; it is visibly different from of the other samples distributions on all diameters.

3.1.1. Granulometric Parameters

Granulometric parameters were determined by calculating the granular class, the fineness modulus and the uniformity and curvature coefficients. Tables 3–5 summarize the calculations results. The granular class of the six samples is 0/4; according to the standard EN 12620, sediment dredged from Safi harbor corresponds to sand. On average, the fineness modulus of dredged sediment is 1.42; according to the standard EN 12620, sediment dredged from Safi harbor is considered as fine-grained sand (F_M between 0.6 and 2.1). The finesses modulus of samples P1, P2, P3 and P4 is included between 0.6 and 2.1; they are considered as fine-grained sands. Samples P5 and P6 correspond to sand of medium to fine grains (F_M between 1.5 and 2.8). The mean value of uniformity coefficient is 2.19; this result is clearly influenced by the excessive value of 4.44 corresponding to sample P1. According to the standard *NF P 18-545*, sediment dredged from Safi harbor has a uniform or close grain size for all samples ($Cu < 2$), with the exception of sample P1, which has a varied or spread grain size ($Cu > 2$). On average, the curvature coefficient is 1.18. Under the standard *NF P 18-545*, the sediment dredged from the port of Safi has a well-graded grain size ($1 < C_c < 3$), excluding the samples P2 and P3, which have a badly graded grain size marked by the presence of a large quantity of fine elements ($C_c < 1$).

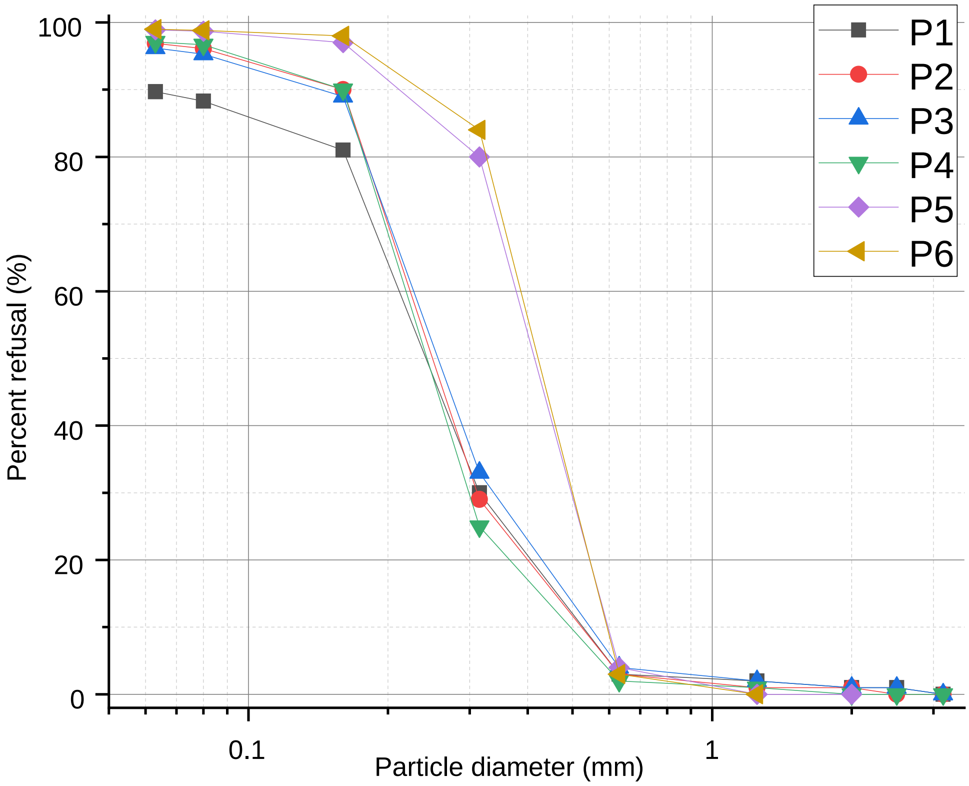

Figure 3. Particle size distribution of Safi harbor sediment.

Table 3. Granular class of sediment dredged from Safi harbor.

Sample	P1	P2	P3	P4	P5	P6	Min	Max	Mean	Median
d	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063	0.063
D	3.15	3.15	3.15	3.15	2	1.25	1.25	3.15	2.64	3.15
Granular class d/D	$D \leq 4$ mm and d = 0									

Table 4. Modulus of fineness of sediment dredged from Safi harbor.

	Sample	P1	P2	P3	P4	P5	P6	Min	Max	Mean	Median
Cumulative mass percentage of refusals (%)	>4 mm	0	0	0	0	0	0	0	0	0	0
	>2 mm	1	1	1	0	0	0	0	3.15	0.5	0.5
	>1 mm	2	1	2	1	0	0	0	2	1	1
	>0.5 mm	3	3	4	2	4	3	2	4	3.17	3
	>0.25 mm	30	29	33	25	80	84	25	84	47	31
	0.125	81	90	89	90	97	98	81	98	91	90
	Fineness modulus F_M	1.17	1.24	1.29	1.18	1.81	1.85	1.17	1.85	1.42	1.27

Table 5. Coefficients of uniformity and curvature of Safi harbor sediment.

Sample	P1	P2	P3	P4	P5	P6	Min	Max	Mean	Median
D_{10}	0.063	0.16	0.16	0.16	0.25	0.27	0.063	0.27	0.18	0.16
D_{30}	0.19	0.21	0.2	0.21	0.35	0.36	0.19	0.36	0.25	0.21
D_{60}	0.28	0.28	0.28	0.26	0.45	0.47	0.26	0.47	0.34	0.28
Cu	4.44	1.75	1.75	1.63	1.80	1.74	1.63	4.44	2.19	1.75
Cc	2.05	0.98	0.89	1.06	1.09	1.02	0.89	2.05	1.18	1.04

3.1.2. Statistical Parameters

Quantile values Q_5, Q_{16}, Q_{25}, Q_{50}, Q_{75}, Q_{84} and Q_{95} were deducted from the grain size curves. Figure 4 gives the distribution of all sample percentiles in unit φ. Distribution curves of the quantiles follow a similar shape, with the exception of quantile Q_{95}, particularly for sample P1. Extreme values of quartile Q_{95} can be substantiated by the presence of more fine particles in sample P1 or to the slight inaccuracies obtained in the case of the incomplete curves for high quantiles such as Q_{84} and Q_{95} [138]. Quantiles corresponding to samples P5 and P6 are visibly lower than the same quantiles of the other samples. The low values of the median Q_{50} reflect the predominance of the sandy fraction.

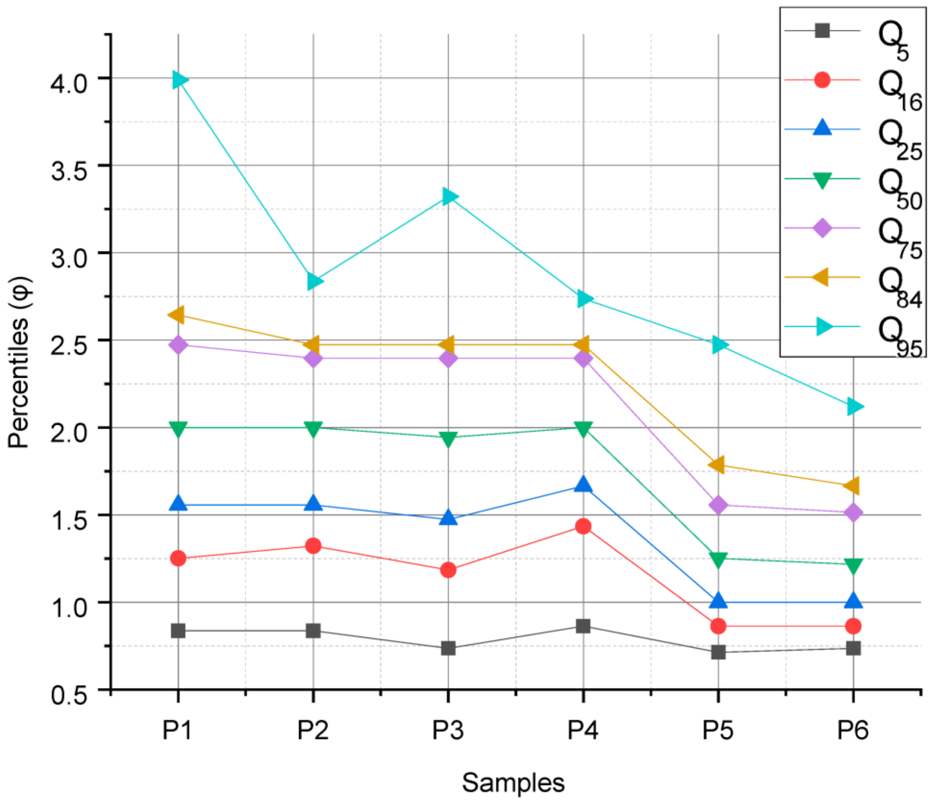

Figure 4. Distribution of particle size quantiles of dredged sediment.

Statistical parameters related to dispersion, asymmetry and acuity were calculated according to the presented formulas. Table 6 gives the results of statistical parameters characterizing the sediment dredged from Safi harbor. Dispersion parameters indicated similarities between the characteristics of samples P1, P2 and P3 on the one hand, and P5 and P6 on the other hand. While sample P4 was characterized by a mean grain of the same range as the first three samples, the sorting index and standard deviation values converged towards those of samples P5 and P6. The mean value of sorting-index is 1.297 mm; the values concerning the six samples were all strictly less than 2.5 mm, which indicates that Safi harbor sediment is well classified. The smaller the index sorting becomes from sample P1 to sample P6, the less accentuated the heterometry. While the mean value of standard deviation is 0.597 φ, reference tables for Folk and Ward index identifies two classes. Samples P1, P2, P3 and P4 are considered moderately classified ($0.5 < \sigma < 1$). Samples P5 and P6 are well classified ($0.35 < \sigma < 0.50$). On average, the mean size is in the range of 0.3 mm. Samples P1, P2, P3 and P4 were characterized by similar mean size values of about 0.25 mm, while samples P5 and P6 had a mean size of about 0.4 mm. The mean value of the Trask asymmetry index was 1.034 mm. All samples had values close to 1; this indicates that sediment dredged from Safi harbor is characterized by a slight asymmetry. Skewness index represented relatively divergent values, with an average of 0.034. The negative values related to samples P2, P3 and P4 indicate the presence of more fine particles. The positive values corresponding to samples P1, P5 and P6 show a better classification of the coarse fraction compared to the fine fraction. The mean value of kurtosis was 1.164, with a range between 0.976 for sample P2 and 1.408 for sample P1; particle distribution is moderately to well classified. The curve is considered mesokurtic for samples P2, P4 and P6 ($0.90 < K_\sigma < 1.11$) and leptokurtic for samples P1, P3 and P5 ($1.11 < K_\sigma < 1.50$). None of the samples is considered misclassified.

Table 6. Dispersion, asymmetry and acuity indices of sediment dredged from Safi harbor.

Sample		P1	P2	P3	P4	P5	P6	Min	Max	Mean	Median
Dispersion	S_0 (mm)	1.374	1.338	1.376	1.288	1.213	1.195	1.195	1.376	1.297	1.313
	σ (φ)	0.826	0.591	0.714	0.544	0.498	0.411	0.411	0.826	0.597	0.568
	M_Z (mm)	0.256	0.262	0.274	0.255	0.406	0.421	0.255	0.421	0.312	0.268
Assymetry	SK (mm)	0.979	1.034	1.012	0.958	0.964	0.946	0.946	1.034	0.982	0.972
	SK_σ (φ)	0.093	−0.170	−0.055	−0.151	0.273	0.211	−0.170	0.273	0.034	0.019
Acuity	K_σ (φ)	1.408	0.976	1.149	1.053	1.297	1.102	0.976	1.408	1.164	1.126

3.2. Physical Characterization

Physical properties of dredged sediment were identified by the results of the tests of water content (w), methylene blue value (MBV), sand equivalent (SE), apparent density ($\rho_{apparent}$) and absolute density ($\rho_{absolute}$). Table 7 represents the physical parameters characterizing Safi harbor sediment.

Table 7. Physical properties of sediments dredged from Safi harbor.

Sample	P1	P2	P3	P4	P5	P6	Min	Max	Mean	Median
w (%)	138	123	127	72	66	36	36	138	93.67	97.5
SE	62	75	73	76	80	92	62	92	76.33	75.5
$\rho_{apparent}$ (g/cm^3)	1.50	1.51	1.51	1.49	1.47	1.43	1.43	1.51	1.48	1.50
$\rho_{absolute}$ (g/cm^3)	2.57	2.60	2.59	2.63	2.63	2.63	2.57	2.63	2.61	2.61
MBV	2.5	0.7	0.8	0.7	0.5	0.5	0.5	2.5	0.95	0.7

(1) Water Content

Dredged sediment water content varied between 36 for sample P6 and 138 for sample P1, with an average value of 93.67%. The high water content is explained by the origin of the sediment, which is taken from a marine area. Water content was higher for samples P1, P2 and P3, located in the harbor exploitation basins, than for the samples located in the access channel (P4, P5 and P6). According to the particle size analysis, the first three points contained more fine particles, which justifies their high water content.

(2) Sand equivalent

The mean value of sand equivalent was 76.33. Test results fluctuated between 62 for sample P1 and 92 for sample P6. Based on values recommended by the literature [139], sediment dredged from Safi harbor is generally clean ($SE > 60$). The cleanliness of the sand increases significantly when moving from the inside basins to the harbor access channel.

The sand in sample P1 was slightly clayey ($60 \leq SE < 70$), of acceptable cleanliness for quality concrete when shrinkage is not a particular concern. Samples P2, P3, P4 and P5 were considered clean ($70 \leq SE < 80$), with a low percentage of clayey fines, sand perfectly suitable for high-quality concrete. Sample P6 was very clean ($SE > 80$), characterized by an almost total absence of clayey fines; it presents the risk of causing a lack of plasticity in the concrete and requires correction by increasing the water dosage. Figure 5 presents an interpretation of the sand equivalent test per sample.

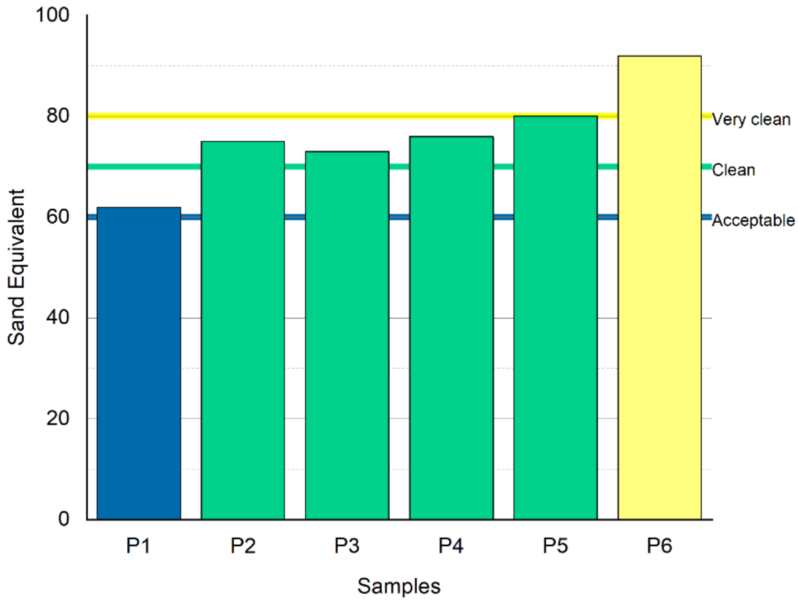

Figure 5. Interpretation of Sand Equivalent of dredged sediment.

(3) Apparent and absolute densities

The apparent density for dredged sediment varied from 1.43 for sample P6 to 1.51 for samples P2 and P3, with a mean value of 1.48. Results of the absolute were very similar for the six samples; on average, dredged sediment absolute density was 2.61. The values obtained confirmed that the dredged sediment meets the requirements for construction ($\rho_{apparent}$ between 1.35 to 1.50 and $\rho_{absolute}$ around 2.65).

(4) Methylene blue value

On average, the methylene blue value was 0.95; this result was clearly influenced by the excessive value of 2.5 corresponding to sample P1. According to the standards in effect, sediment dredged from Safi harbor has a sandy-loamy nature sensitive to water ($0.2 \leq MBV < 1.5$), with the exception of sample P1, which had a loamy nature characterized by medium plasticity ($2.5 \leq MBV < 6$).

3.3. Chemical Characterization

Chemical analysis was performed to study the reaction of dredged sediment as a concrete aggregate. The contents of chloride and sulfate, considered as contaminants, were calculated. Figure 6 shows the test results and their comparison with the accepted threshold values for the aggregates according to the standard XP P18-545. The chloride content varied between 0.15% and 0.18%. For all samples, chloride content was high; it exceeded the reference threshold. The high chloride content was justified by the marine origin of the sediments; seawater contains dissolved substances, i.e., salts consisting of ions, mainly halide ions such as chloride ion and alkaline ions such as sodium ion. The sulfate content was below the reference threshold for all samples; it ranged between 0.05% and 0.12%.

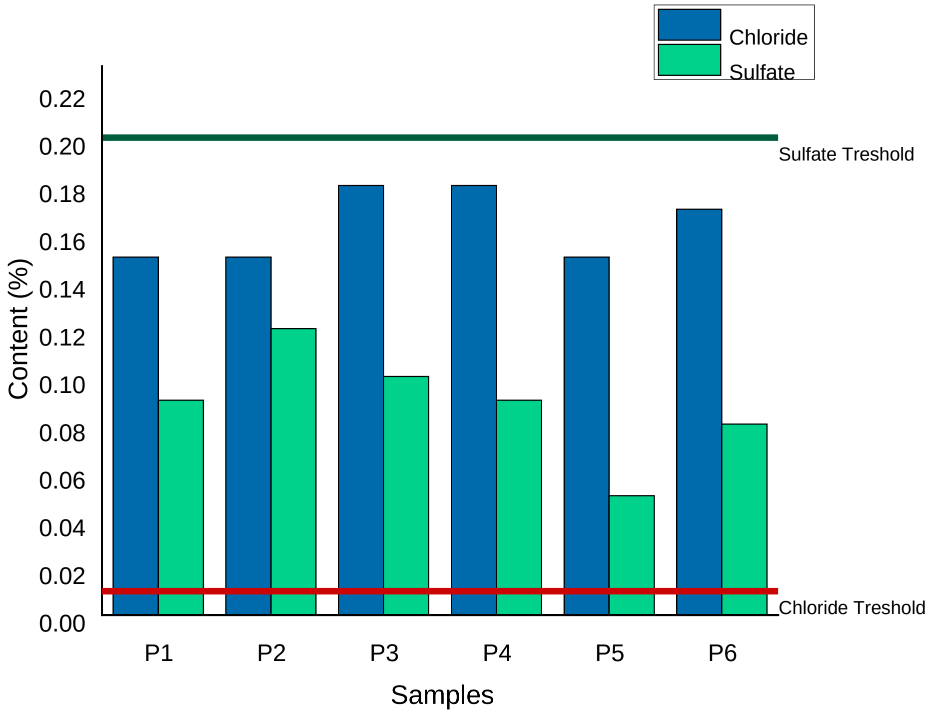

Figure 6. Chloride and Sulfate contents of dredged sediment.

3.4. Mineralogical Characterization

A mineralogical analysis of the studied sediment was carried out. As the sediment dredged from Safi harbor has the same origin, i.e., the erosion by sea of the neighboring dunes and beaches, the mineralogical composition is in principle the same in all the basins of the port. To confirm this hypothesis, two tests were carried out: first, one on the mixture of samples taken from P1, P2 and P3 (SF1), and a second one on the mixture of samples taken from P4, P5 and P6 (SS2). Quartz SiO_2 and Calcite $CaCO_3$ were found to be the two main crystalline phases. Figure 7 presents X-ray Diffractograms of mixtures SF1 and SS2.

3.5. Cost-Benefit Analysis

For the purpose of studying the economic feasibility of dredged sediment reuse as construction material, costs of the various items were estimated according to the current Moroccan market, and then converted into dollars to allow a better assimilation to the international market. To obtain the final cost of recycling dredged sediment, basic hypotheses have been established as follows:

(1) Costs considered

- Dredging cost: this cost includes the expenses related to regular dredging operation to maintain the depths of the port basins;
- Port storage cost: the cost of renting land in the port for the storage of dredging material (for characterizing, washing, dehydrating, etc.);
- Characterization cost: the sum of the costs of all the tests carried out to obtain an appropriate material to be reused in construction;
- Treatment cost: the cost of artificial fresh-water washing to remove impurities from the dredged sediment;
- Loading/unloading cost: costs associated with loading the sediment for delivery outside the port and unloading at the final point of sale;
- Transportation cost: expenses related to the transportation by truck of the sediment from the port to the distribution point;
- Final storage cost: the cost of renting land in a rural area of the Safi region (for distribution, sale, etc.);

- General expenses: costs related to the installation, staff, material, etc.

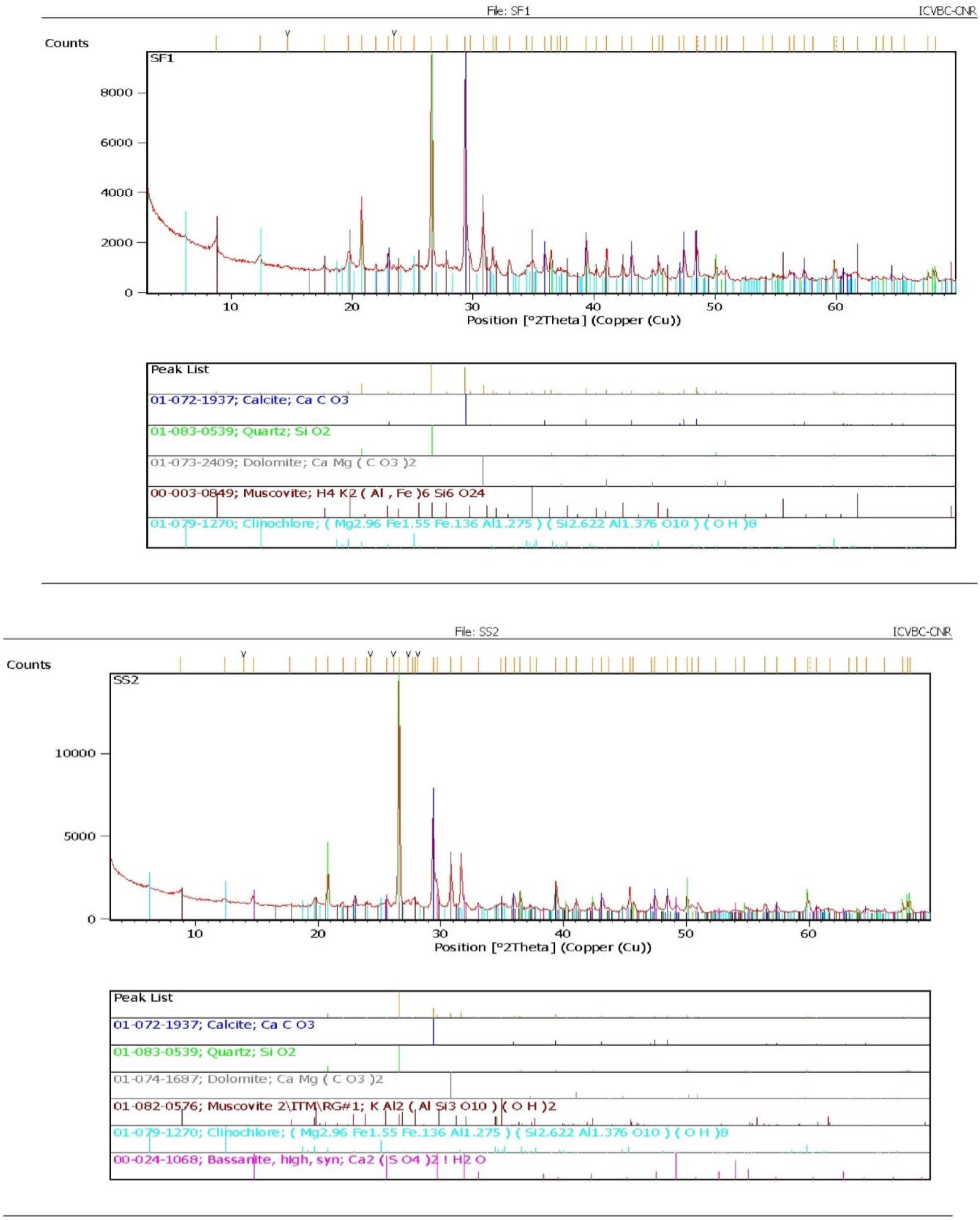

Figure 7. X-ray Diffractograms of dredged sediment.

It is worth noting that none of these costs depend on the point of collection or the dredging area in the port; therefore, it is not necessary to perform a site-specific cost-benefit analysis, which will lead to the same result.

(2) Costs estimation

The cost of dredging is calculated by reference to the unit prices, per cubic meter, applied in Morocco. The cost of storage in the port is calculated on the basis of the rates for temporary occupation of the public port domain for a 1000 m^2 land plot. Characterization cost is inspired by the modalities applied in the case of quarries extracting aggregates for construction, in order to confirm the regularity and stability of the properties identified. The cost of characterization includes the costs of all the characterization tests conducted by this study once every two years, and the costs of tests of grain size analysis and sand equivalent once every 100 m^3. The treatment cost is calculated based on fresh-water consumption rates. The cost of loading/unloading is calculated according to the current rates applied by truckers. Transportation cost is calculated based on current fuel rates for an estimated distance of 25 km. The final storage cost is calculated based on the rental rates for a 1000 m^2 plot of land in a rural area. All costs are reported per cubic meter to enable summation.

The purchase cost corresponds to conventional sand used in civil engineering, with the same granulometric characteristics as that of the sediment extracted from the port of Safi. Table 8 summarizes the calculations made to analyze the cost-benefit of reusing harbor dredged sediment as construction material. Results from the cost evaluation show that dredged sediment reuse is the most cost-effective option, with a reduction of 74% compared to the purchase of conventional material.

Table 8. Cost-benefit analysis of dredged sediment reuse.

Item	Corresponding Cost ($/m^3)	Total Recycling Cost ($/m^3)	Conventional Material Cost ($/m^3)	Difference (%)
Dredging	5.00	11.52	25.00	74%
Port storage	0.01			
Characterization	0.20			
Treatment	2.00			
Loading/unloanding	0.07			
Transportation	1.70			
Final storage	0.04			
General expenses	2.5			

4. Discussion

4.1. Dredged Sediment Characterization and Classification

Compared with previous studies, this study justified the choice of laboratory tests for the characterization of dredged sediment, which allows for its optimization for widespread use in developing countries. We opted for a port that is experiencing a high level of silting and therefore requires regular dredging. Safi port generates large quantities of dredged sediment, which offers an opportunity for further recycling. Obtaining construction material in large quantities justifies the investments related to its production based on dredged sediment. In order to reflect the real characteristics of the sediment and to obtain the best informational value on its performance as a potential construction material, the sampling plan was chosen to cover all the areas concerned with dredging in the port of Safi. Careful attention was paid to the conditions of sample collection and storage to prevent any impact on the test results. Due to the absence of reference values, this study repeated the laboratory tests carried out, as well as the calculations of statistical parameters, to confirm the results obtained.

Since sedimentological studies of the region provide an indication of the nature of sediment dredged from the port of Safi, we selected the characterization tests usually carried out to determine the properties of conventional sand used as an aggregate for concrete. The result of this choice included the essential tests for the characterization of dredged sediment, which are within the means available in developing countries. Laboratory tests were completed using the calculation of statistical parameters, in order to provide an integral overview of sediment properties and to confirm experimental results. As it constitutes a primordial and decisive step in the valorization process, the characterization of physical, geotechnical, chemical and mineralogical properties was conducted. Characterization by sampling point allowed for the identification of the properties of the material dredged from each basin, not only for commercialization purposes, but also to compare the characteristics of the sediment from one site to another. The classification of the sediment according to the applicable standards is based on the average values of the studied parameters while neutralizing the excessively high or low values justified. The sediment of Safi harbor is identified as sand with medium to fine grains (about 90% between 0.315 mm and 1.25 mm). It represents a uniform and well-graded grain size. Sandy fraction is predominant, featuring well-classified particles with a slight asymmetry. The mean grain size is about 0.3 mm. Dredged sand is sensitive to water, and generally clean with a low percentage of clayey fines. Particle distribution is moderately to well classified. Significant water content (about 94%) and a high concentration of chloride (between 0.15% and 0.18%) are explained by the salty marine origin. Moreover, sulfate content is negligible. The main mineralogical phases are Quartz and Calcite. Comparing the properties of Safi port sediment to those of previous studies on the characterization of marine sediment, particularly for reuse in the construction industry, there is a wide range in the values found from one study to another. However, most studies show that dredged sediments have common properties, such as the fineness of their particle size and the high contents of water and chloride mainly due to their marine origin. Table 9 summarizes the comparison of characterization parameters from this study with literature values derived from studies conducted on sediments rather similar to those dredged from the port of Safi.

Table 9. Comparison of characterization parameters with literature values.

Parameter	Value from This Study	Value Found in the Literature	Difference (%)
Water content (%)	93.67	63.5 [140]	38
Fineness modulus	1.42	1.635 [141]	14
Granular class	0/4	0/4 [24]	0
Uniformity coefficient	2.19	2.20 [142]	0
Curvature coefficient	1.18	1.01 [142]	16
Mean size (mm)	0.312	0.4 [114]	25
Sorting-index (mm)	1.297	1.5 [143]	15
Skewness (φ)	0.034	0.01 [143]	109
Standard deviation (φ)	0.597	0.7 [143]	16
Sand Equivalent	76.33	66.32 [141]	14
Apparent density (g/cm^3)	1.48	1.52 [141]	3
Absolute density (g/cm^3)	2.61	2.45 [140]	6
Methylene blue value	0.95	0.82 [78]	15
Chloride content (%)	0.16	0.13 [92]	21
Sulfate content (%)	0.09	0.16 [92]	56
Mineral composition	SiO_2, $CaCO_3$	SiO_2, $CaCO_3$ [92]	0

On the whole, according to the standards of concrete aggregates classification, and except for the contents of water and chloride, sediment dredged from the port of Safi is a sand classified into category B, related to the sands used for the confection of current concretes of resistance higher than 25 MPa. As for the variation of properties from one sample to another, sediment properties slightly differ; a remarkable improvement is observed when passing from the interior basins of the port towards its access channel. The industrial and urban activity of the port seems to influence the characteristics of sediment from exploitation basins.

4.2. Prerequisites for Dredged Sediment Reuse

For reuse as construction material, particularly as concrete aggregate, high contents of water and chloride influence the durability of final products. It is necessary to reduce these components by appropriate treatment. Dredged sediment is considered wet because of its high water content. Therefore, it can't be used in its raw form as concrete aggregate; it is too wet to be appropriate for enhancement with additives. Natural dehydration, in the sun, of dredged sediment of the port of Safi is necessary in order to reduce water content. Moreover, corrosion occurs when chloride ions come into contact with steel and nearby passive material; a chemical reaction produces hydrochloric acid. The hydrochloric acid attacks the steel reinforcement, causing the concrete to crack, splinter and break [144]. This issue limits the use of dredged sediment in unreinforced concrete. Hence, for the manufacturing of reinforced and prestressed concrete, it is necessary to reduce the chloride content with appropriate washing with fresh water. Rain flushing or artificial washing would most certainly reduce the chloride level to tolerable limits [122]. Washing with fresh water and then dehydrating dredged sediment is sufficient to recycle a valuable substitute to conventional sand and concrete aggregate. Natural dehydration will then take place after washing. These treatments involve the storage of the sediment in the port near its dredging site. Then, the treated sediment must be transported outside the port for commercialization.

4.3. Economic Feasibility

The economic feasibility of dredged sediment reuse was examined as a part of assessing the possibility of implementing the production of concrete aggregate as a substitute to conventional sand. By comparing the costs of sediment reuse with commercial sand, it was observed that dredged sediment is cost efficient as an aggregate source. There are only few estimates of dredged sediment recycling in the literature. Most studies in developed countries have focused on the cost of treating dredged sediment for environmental reasons [17,145,146]. The concept of reusing dredged sediment appears attractive because of the potential economic benefit of eliminating the costs associated with dredged sediment disposal and construction material importation [147]. Concrete projects have shown that the reuse of dredged material is cost saving, such as the British Waterways business unit project in Yorkshire, which saved an estimated $2.1 million [59], and the Embraport container terminal project in Brazil, which achieved savings of about $50 million by reusing dredged sediment [147]. A comparison of the costs considered for sediment recycling between this study and previous studies shows some similarities. For example, Kupryianchyk [148] estimated dredging cost between 1.04 and 7.25 $\$/m^3$ depending on the type of surface water, the thickness of the sediment layer to be extracted and differences in operating conditions. Transportation cost by truck was about 0.16 $/ton of wet sediment/km [148]. These charges are among the main costs of sediment recycling. Figure 8 represents the cost structure for reusing dredged material. Dredging, transportation, treatment and general expenses are the costliest (about 97% of the final cost). In sum, sustainable reuse of harbor dredged sediment as construction material is cost saving.

4.4. Potential Pathways for Dredged Sediment Reuse

Beneficial reuse of dredged sediment as construction material presents financial and non-financial gains. To face the scarcity of natural granulates used in the construction industry, sediment dredged from the port of Safi could be viewed as a stable source of sandy aggregate. Large amounts of sediment, currently disposed of at sea as waste, are readily reusable in the form of construction aggregate. In its raw form, sandy sediment can be adapted to conventional construction work. Dredged sediment could potentially be used for the construction of embankments and backfilling, which require significant quantities of material.

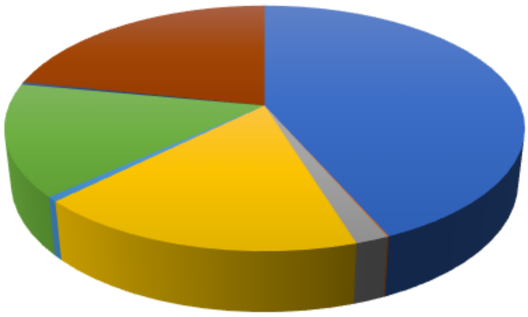

Figure 8. Cost structure for the reuse of dredged material.

A treatment is possible to reduce chloride and water content and expand the use of dredged sediment in other applications related to the construction industry. It can then be used for mortar manufacture, brick production and road techniques. Nevertheless, concrete remains the most cost-effective and versatile material assembly used in construction projects; it can form all structural elements, even the most complex and resistant shapes, when used with steel reinforcement [122]. Moreover, the costs associated with its manufacture are considered important. Based on the characterization performed, dredged sediment properties meet construction requirements. It can be used, after treatment, in concrete works requiring high resistance. Reusing dredged sand as concrete aggregate is the most recommended path for the case study of the port of Safi.

4.5. Limitations and Further Work

Dredged sediment of the port of Safi was characterized and classified according to construction standards. A cost-benefit analysis was performed to study the economic feasibility of its use. The results suggested that the beneficial reuse of dredged marine sediment as concrete aggregate offers a possible alternative to conventional sand. It will help to avoid sand extraction, which results in environmental and ecological problems. However, there are some limitations to this study. The obtaining of a high-strength concrete is evaluated based on the characteristics of the sediment according to the standards in application. Further research on the concrete developed using dredged sediment as a sand substitute is required to study its properties. At the same time, a detailed price study including all the components related to operating procedures is more conducive to our in-depth evaluation of the feasibility of the beneficial reuse of dredged sediment as a concrete aggregate.

5. Conclusions

Waste valorization represents a sustainable way to face the scarcity of natural resources used in the construction industry. Large amounts of dredged sediment are extracted annually and disposed of at sea; this constitutes a potential alternative to conventional construction material. Furthermore, the valorization of dredging waste avoids the environmental impacts associated with its disposal at sea and with the extraction of natural resources from the soil. In this study, we characterized sediment dredged from Safi harbor in Morocco for reuse as construction material. Due to its high level of silting, Safi port offers an opportunity for further recycling of its sediment dredged in significant quantities. Six samples were collected to cover all the port areas. The choice of laboratory tests was based on the essential tests usually performed for the characterization of dredged sediment, taking into consideration the means available in developing countries. Laboratory tests were completed using the calculation of statistical parameters, in order to provide an integral overview of sediment properties and to confirm experimental results. As it constitutes a primordial and decisive step in the valorization process, the characterization of physical, geotechnical, chemical and mineralogical properties was conducted. The results showed that, according to the standards of construction material classification, sediment dredged from the port of Safi is a sand classified into category B, related to the sands used for the confection of current concretes of resistance higher than 25 MPa. Therefore, the studied sediment is readily reusable in the form of a construction aggregate as a conventional sand substitute. Chloride and water content was obviously higher than reference levels, mainly because of the sediment's marine origin. Sediment properties slightly differed from one sample to another; a remarkable improvement was observed when passing from the interior basins of the port towards its access channel. The industrial and urban activity of the port seems to influence the characteristics of sediment extracted from exploitation basins. The obtained classification allows the beneficial reuse of dredged sediment in several applications in the construction industry. We were interested in concrete works; concrete remains the most cost-effective and versatile construction material. In addition, treatment was suggested to reduce the content of chloride that promotes corrosion in reinforced concrete, and thereby limits the use of dredged sediment to unreinforced concrete. Reuse of dredged sand as a concrete aggregate was then the most recommended path for the case study of the port of Safi.

Subsequently, a comprehensive evaluation of economic feasibility was carried out based on a cost-benefit analysis. The costs related to the valorization of sediment dredged from Safi port were analyzed and compared with the cost of purchasing conventional sand of the same class. The purchase cost remains higher than the cost of recycling with a decrease of 74%, which indicated that the beneficial reuse of dredged sediment as construction material is cost saving and presents financial and non-financial gains.

Therefore, promoting a holistic view of prerequisites for the valorization of dredged sediment in developing countries—such as selecting ports that generate significant quantities of dredged sediment, standardizing characterization tests during dredging operations, and estimating the cost of recycling taking into account the necessary treatments—is encouraged to meet the market's need for construction material.

This study contributes to a deeper understanding of the process evaluating the feasibility of reusing dredged sediment as construction material for research in other developing countries. A thorough characterization of the dredged waste is crucial to the identification of potential recycling paths for achieving sustainable development.

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