buildings

MDPI

Article

Stabilization and Recycling of Sand in Pedestrian Walkways

Mazhar Hussain [1,*], Hafida Zmamou [2], Antony Provost [3], Paula Andrea Higuera Romero [1], Angélique Mahieu [1], Nathalie Leblanc [2], Daniel Levacher [4] and Abdoulaye Kane [1,*]

1 UniLaSalle-Ecole des Métiers de l'Environnement, Cyclann, Campus de Ker Lann, 35170 Bruz, France; angelique.mahieu@unilasalle.fr (A.M.)
2 UniLaSalle, Université d'Artois, EA7519—Transformations & Agro-Ressources, Normandie Université, 76130 Mont Saint Aignan, France; hafida.zmamou@unilasalle.fr (H.Z.); nathalie.leblanc@unilasalle.fr (N.L.)
3 GENDROT TP, Z.A. de Bel-Air, 35320 Crevin, France; antony.provost@gendrot-tp.com
4 Unicaen, UMR 6143 CNRS—M2C, Normandie Université, 24 Rue des Tilleuls, 14000 Caen, France; daniel.levacher@unicaen.fr
* Correspondence: mazhar.hussain@unilasalle.fr (M.H.); abdoulaye.kane@unilasalle.fr (A.K.)

Abstract: The production of construction and demolition waste (CDW) in urban areas is growing rapidly. While the storage and disposal of CDW waste is costly, its recovery can help to conserve natural resources. This study investigates the characteristics of recycled sand obtained from the processing of CDW waste and the possibility of its reuse for pedestrian pathways. Physico-chemical and mineralogical characteristics of the recycled sand were investigated for its reuse. The percentage of fine particles in sand (below 0.63 µm) is 2.8%. The grain size of sand fulfills the particle size requirement of French standards. The methylene blue value of sand is 0.05 g/100 g. The GTR classification of recycled sand is D2 which is insensitive to water and suitable for road applications. A mineralogical analysis of soil shows that quartz, albite and microcline are important minerals in recycled sand. XRF analysis shows that CaO and SiO_2 are major oxides in the recycled sand. The characterization of sand was followed by a manufacturing of cylindrical specimens of sand to observe the compressive strength. Samples were compacted with dynamic compaction by applying the Proctor normal energy of 600 kN·m/m^3. The compressive strength testing of specimens shows that non-stabilized sand samples have compressive strength around 0.1 MPa which is considerably lower for its reuse in pedestrian pathways and road applications. Due to the low bearing capacity of sand, recycled sand was stabilized with the addition of binders such as Rolac (hydraulic binder), ground-granulated blast furnace slag (GGBS) and ECOSOIL® (slag mixes) with different percentages of the binder ranging from 0 to 7% for the optimization of the binder and for economic efficiency. The compressive strength of sand samples increases with the increasing percentage of the binder. The increase in strength is more important with a higher percentage of binders (5%, 6% and 7%). At a 7% binder addition, specimens with Rolac, GGBS and ECOSOIL binders show the compressive strength of 1.2 MPa, 0.5 MPa and 0.5 MPa. At a 7% Rolac addition, specimens have a compressive strength higher than 1 MPa and meet the strength requirement for soil reuse in the foundation and subbase layers of roads with low traffic. The experimental work shows that recycled sand can replace conventional quarry sand for road applications and pathways with the addition of a local binder, which is an eco-friendly and economical practice.

Keywords: recycled sand; waste management; waste recovery; pedestrian pathways

check for updates

Citation: Hussain, M.; Zmamou, H.; Provost, A.; Romero, P.A.H.; Mahieu, A.; Leblanc, N.; Levacher, D.; Kane, A. Stabilization and Recycling of Sand in Pedestrian Walkways. *Buildings* **2024**, *14*, 205. https://doi.org/10.3390/buildings14010205

Academic Editor: Daxu Zhang

Received: 17 November 2023
Revised: 3 January 2024
Accepted: 10 January 2024
Published: 12 January 2024

Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https://creativecommons.org/licenses/by/4.0/).

1. Introduction

The building sector is one of the biggest consumers of natural resources and producers of construction and demolition (CDW) waste in France and all around the world. A huge quantity of construction and demolition waste is generated annually across the globe. The annual production of construction and demolition (CDW) waste in France is nearly 246.7 million tons [1]. CDW is mainly produced by building activities and the demolition

of existing structures and waste from concrete manufacturing plants [2]. Every year, a significant amount of this waste is disposed of on land sites which is becoming costly and harmful to the environment due to its huge volume, leaching and soil pollution. In addition, the French government is focusing on decreasing the landfill disposal of construction and demolition waste. The Bretagne Region of France aims to have zero landfill by 2030 and zero waste by 2040 [3]. Furthermore, the French government implements extended producer responsibility for buildings by implementing a special tax for ecological contribution on construction companies to eliminate their waste [4].

Overconsumption of natural resources, including sand, is another challenge faced by the construction industry in France and Europe. Every year, nearly 40 to 50 billion tons of sand is used in the construction industry in France. Most of the sand is mined from quarries. The excessive use of sand in building and infrastructure projects is leading to its depletion [5]. The remoteness of quarries for mining sand from the urban areas increases their transportation cost and emission of greenhouse gases. Higher CO_2 emissions, the use of nonrenewable resources and increasing costs of aggregates and sand have encouraged us to look for recycling construction and demolition waste.

The processing of CDW waste helps to produce recycled aggregate and sand. France produces nearly 28.1 million tons of recycled aggregate from construction and demolition waste annually [6]. In the Brittany region of France, nearly 0.2 million tons of recycled aggregate is produced annually, which is the lowest among all the regions of France [7]. In the Brittany region of France, 46% of actors find the production of recycled sand and aggregate profitable. The cost-effectiveness of recycling construction and demolition waste depends on several factors, including the proximity of quarries and waste processing platforms. The cost of waste disposal, closeness of recycling platforms to the waste generation and the primary material consumption areas make the recycled sand and aggregate competitive alternatives to conventional materials [8]. Furthermore, the production of one ton of recycled aggregate produces 40% less than greenhouses compared to the production of one ton of natural aggregate [6].

The fine fraction of CDW waste (0/4.8 mm) represents nearly 50% of the total demolished waste [9]. Recycled sand is primarily used for roads, concrete and backfill applications [10]. Characteristics of recycled aggregate are important for its reuse and they are heavily influenced by the nature of CDW waste, its processing method and the presence of impurities such as sulfate, chlorides, etc., which affect aggregate quality and limit its use for structural and high-strength concrete [11,12]. For structural concrete, French standards recommend a maximum of 30% replacement of natural aggregate. In addition, the texture of recycled sand and its higher sulfate content in recycled sand make it undesirable for concrete [13]. Some important characteristics of recycled sand and aggregate include mineralogy, grain size, porosity, absorption capacity, the presence of soluble sulfates, total sulfur, chlorides, alkali reaction etc. [14]. Recycled aggregate including sand has higher porosity and higher water absorption, which needs special attention for its reuse [15].

Sand is usually used in the foundation and subbase layer of the road. Another application of sand reuse is pedestrian pathways, which are separated from roads to ensure the safety of pedestrians [16]. Pedestrian pathways can be built with concrete, asphalt and fine aggregates (sand). However, asphalt and concrete pavements have a higher environmental impact and they prevent the recharging of groundwater, as they are impermeable. Pedestrian pathways with natural soils having higher clay content are slippery in rainy seasons and produce dust in dry seasons [17]. Therefore, appropriate soil selection is essential to make pathways to ensure mechanical resistance and to support the expected loads [18].

The stabilization of sand is conducted to increase its strength and make it suitable for pedestrian pathways, sidewalks and playgrounds, etc. In the case of pedestrian pathways, natural soil is removed and replaced with a layer of aggregate and stabilized soil. The stabilization of sand helps to make non-slippery pathways with significant wear resistance. The stabilization of sand can be achieved through mechanical means and with the addition of binders [19].

The engineering characteristics of sand are improved with the addition of cementitious binders by increasing the strength and stiffness of stabilized soils [20]. Furthermore, the addition of the binder increases the bearing capacity and shear strength of the soil, reduces its permeability and limits the settlement [21]. The addition of the binder reduces the dust and influences the color of pathways. Some common binders are cement, lime and geopolymers, etc. The mechanical strength of sand composites depends on the type of sand, its granulometry, the percentage of fine particles and the binder used. The higher percentage of fine particles in sand leads to the water absorption and swelling of sand which decreases its strength [5].

Due to the lack of awareness in the construction sector and lack of collaboration between academia and enterprises, public works companies in the Brittany region, France use mostly quarry sand stabilized with the traditional binder (cement) for the construction of pathways. In addition, recycling platforms for construction and demolition waste are relatively recent developments in Brittany. We have focused on the reuse of recycled sand for pathway construction. The objective of this study is to investigate the physico-chemical and mineralogical characteristics of recycled sand from the Brittany region of France for its recovery in pedestrian pathways. The use of recycled sand and its stabilization with a local binder will help to minimize the use of quarry sand and provide an ecological and low-cost material for pathways and road applications, contributing to the socio-economic development of the region through a sustainable development perspective. In addition, the optimization of the binder content is also focused on achieving the targeted sand resistance with economic and environmental approaches.

2. Materials and Method

The crushing and grinding of CDW waste produce fine and coarse aggregate that can be used in several applications including concrete, roads, backfill, etc. Figure 1 shows the CDW waste storage at the site of Gendrot Entreprise. The CDW waste is sorted to remove the metals and processed to produce fine (0/4 mm) and coarse aggregates (i.e., 4/14 mm, 0/30 mm, 0/100 mm, etc.) The crushing and grinding of CDW waste and the stockpiles of fine (sand) and coarse fractions at the recycling platform can be observed in Figure 1.

Figure 1. Transformation of CDW waste into coarse and fine aggregates.

2.1. Recycled Sand

The recycled sand used in this study comes from the crushing of concrete blocks at the crushing and grinding platform in Rennes, France. The CDW waste at the recycling platform is processed into the coarse aggregate (4 mm, 16 mm, 31 mm, etc.), and the fine aggregate also called recycled sand. The recycled sand fraction has a size from 0 to 4 mm and, due to its texture, its primary application is road materials; it is not well-suited for structural concrete. A stockpile of recycled sand is shown in Figure 1. Physico-chemical and mineralogical characteristics of recycled sand (0/4 mm) recovered from CDW waste were investigated for its reuse in road applications. These characteristics include grain size, moisture content, soluble sulfates and mineralogy. The grain size distribution of soil was investigated according to French standards [22]. The initial moisture content of the sand was measured according to the standard [23]. The optimum moisture content of sand was determined with the Proctor test [24]. Soluble sulfates in recycled sand were determined through the gravimetric method [25]. The mineralogy of sand was determined with an X-ray diffraction technique that is commonly used to find the minerals' content of different materials.

2.2. Binder

The stabilization of sand is essential to improve its strength and geotechnical characteristics [26]. Different types of binders are suggested in French norms including cement, ground-granulated blast furnace slag (GGBS), fly ash, lime, etc., to stabilize the soil for road applications. The suggested dosage of the binder varies with the type of hydraulic and pozzolanic binder, i.e., cement from 4 to 8%, a hydraulic binder from 4 to 5% and activated GGBS from 10 to 20% [27]. Three types of local binders were used in this study to stabilize recycled sand which are Rolac (Lafarge Cement, France) GGBS (Ecocem, France) and ECOSOIL® (slag mixes) (ANT, France). The effectiveness of different binders including Rolac, GGBS and ECOSOIL® in stabilizing recycled sand for pathways' applications is evaluated with different formulations.

Rolac is a hydraulic binder manufactured by Lafarge Cement (Saint-Pierre-la-Cour, France), for the treatment of soils to improve the bearing capacity and resistance of soils. The second binder used is the ground-granulated blast furnace slag (GGBS) with the commercial name of Ecocem, which comes from the Ecocem enterprise from Dunkirk, France. GGBS is an industrial by-product attained from the blast furnace of steel production units. Carbon emissions for GGBS are considered zero, as it is an industrial by-product. It is mainly composed of oxides of calcium, magnesium, aluminum and silicate. The other binder used is ECOSOIL®, which is a mixture of steel slags. The choice of binder is based on local availability, carbon emissions and cost [28].

2.3. Manufacturing of Specimens

The characterization of recycled sand was followed by its stabilization with different binder dosages to optimize the mechanical properties and minimize the cost. The sand and binder were mixed, and an optimum water content was added to make a homogenous mixture. Cylindrical specimens of stabilized sand that were 4 cm in diameter and 8 cm in height, with a slenderness ratio of 2, were manufactured with a binder addition of 0% to 7%, which is the suggested quantity of binders to stabilize soils in accordance with industrial recommendations and literature studies [20,29]. Three specimens were manufactured for each formulation to observe the average mechanical strength through unconfined compressive strength (UCS) tests on a laboratory scale. Recycled sand and binders were mixed with optimum moisture content and compacted with dynamic compaction through the Proctor normal energy of 600 kN·m/m^3, which increases the strength and densification of specimens by re-arranging soil particles [26,28]. Specimens were manufactured with different formulations to optimize the strength of samples and dried for 14 days, instead of the usual drying time of 28 days, because it is important for road materials to achieve

a significant strength as soon as possible. The different formulations used are shown in Table 1.

Table 1. Formulations of stabilized sand.

Binder	Rolac	ECOSOIL®	GGBS
References	S0, R1, R2, R3 R4, R5, R6, R7	S0, E1, E3 E5, E7	S0, G1, G3 G5, G7

Note: S0 = Reference sample with 0% binder; R1 = Sample with addition of 1% Rolac binder, R2 = Sample with 2% Rolac binder . . . . . R7 = Sample with 7% Rolac binder; E1 = Sample with 1% ECOSOIL® biner and E7 = Sample with 7% ECOSOIL® biner; G1 = Sample with the addition of 1% GGBS binder and G7 = Sample with addition of 7% GGBS (Ecocem) binder.

Figure 2 shows the manufacturing and drying of specimens. Figure 2a shows the sand and Rolac binder used to manufacture the samples; Figure 2b shows the mixing of sand with Rolac. Figure 2c shows the specimen preparation with compaction. Figure 2d shows the drying of demolded specimens.

Figure 2. Sand and binder (**a**), sample preparation (**b**), manufacturing of samples (**c**) and cylindrical samples (**d**).

2.4. Testing of Specimens

The compressive strength (UCS) of stabilized sand was found with the Shimadzu AGS-X model machine by using 200 N and 50 kN sensors. Figure 3a shows the testing of cylindrical specimens and the failure under compression in recycled sand specimens. Figure 3b shows a typical stress–strain curve of a cylindrical specimen.

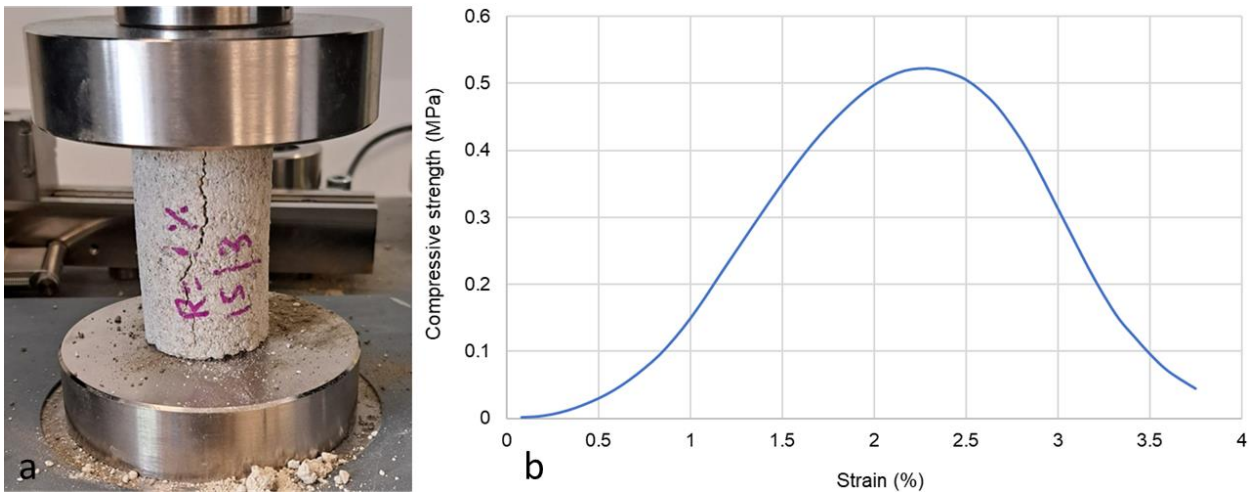

Figure 3. Compressive strength test of a specimen (**a**) and typical stress–strain behavior (**b**).

3. Results and Discussion

3.1. Physico-Chemical Characteristics of Sand

The recycled sand used in this study comes from demolished concrete and is composed of inert and non-dangerous materials that can be used for uncoated roads, coated roads and soil cover [30]. Physico-chemical characteristics of recycled sand recovered from the Gendrot platform were determined through different tests and are shown in Table 2.

Table 2. Physico-chemical characteristics of CDW recycled sand.

Size	Wi (%)	Particles below 0.063 mm (%)	Particles below 4 mm (%)	D_{max} (mm)	Classification GTR	SS (%)	MBV (g/100 g)	OWC (%)	ODD (g/cm^3)	IBI
0/4 mm	7.2	2.8	98	8	D2	0.51	0.05	11.3	1.8	35.1

Note: Wi = initial moisture content, SS = soluble sulfate, ODD density = optimum dry density, OWC = optimal water content, MBV = methylene blue value and IBI = immediate bearing capacity index found by [31].

Table 2 shows that the initial moisture content of recycled sand is around 7%, which is variable with weathering conditions. The immediate load bearing (IBI) value of non-stabilized sand is around 35.1, which is the limit for stabilized sand reuse in the foundation layers of roads; it depends on traffic [27]. The grain size of the sand shows that fine particles of size below 0.063 mm are around 2.8%, which shows that the percentage of clay and silt in recycled sand is very low. However, a certain amount of clay usually improves the bonding of sand and increases its mechanical strength. The grading and shape of the aggregate have a significant influence on the workability, mechanical strength and durability of concrete, and are influenced by the nature of the CDW waste and crushing system adopted [32]. The grading curve of the recycled sand is shown in Figure 4.

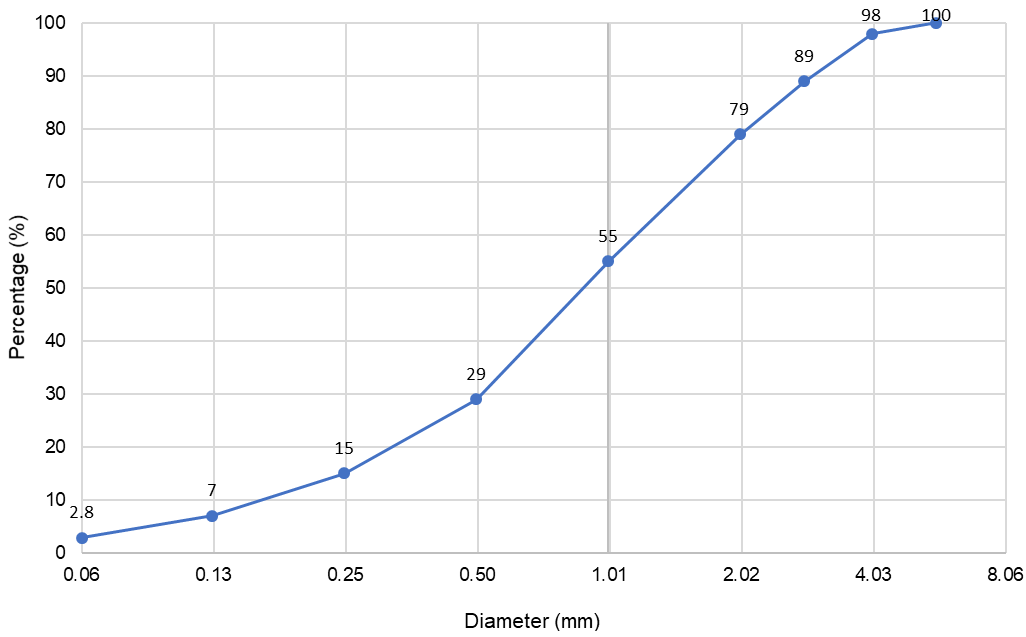

Figure 4. Grain size distribution of recycled sand.

Figure 4 shows that the percentage of fine particles in recycled sand with a diameter below 80 µm is around 5%. According to the French Technical Guide [33], soils with fine particles of 80 µm below 12% are considered poor in fine particles. The grain size of recycled sand in Figure 4 is within the suggested grain size range in the French standard for 0/4 mm sand reuse in construction materials which recommends the percentage of fine particles

below 0.063 mm should be below 6.1% while the percentage of coarse particles of 4 mm should be higher than 89% [34].

Table 2 shows that the methylene blue value (MBV) of sand is around 0.05 g/100 g. The classification of soil in the French standard [35] is D2, as the MBV value of soil is below 0.1 and the percentage of fines (below 80 µm) is nearly 5%; these types of soil are insensitive to water [33,35]. Soluble sulfates in recycled sand are 0.51%, which is below the 1.3% maximum authorized limit in French standards for the reuse of recycled aggregates in road applications [25]. The presence of sulfates and chlorides in recycled sand leads to ettringite formation and a decrease in strength, and limits the perspective of reuse of this aggregate for structural applications due to the swelling of sulfate in rich soils [36,37].

The investigation of mineralogy and oxides in sand is important to observe the composition of recycled sand and select a suitable stabilizing agent. The mineralogy of sand was determined with XRF and XRD techniques. Table 3 shows the oxide composition of recycled sand.

Table 3. Oxide composition of recycled sand.

Unit (%)	SiO_2	CaO	AL_2O_3	Fe_2O_3	K_2O	Others
Sand	45.5	38.4	4.6	4.6	2.6	4.3

Table 3 shows that silica and calcium oxide are major oxides in sand samples. The higher calcium oxide (CaO) content in recycled sand results from cement in concrete. Similar observations were made in research studies [38,39]. Sand is usually composed of silicate minerals such as quartz, feldspar and mica [40]. The mineralogy of recycled sand was studied with X-ray diffraction (XRD). The diffractogram of recycled sand in Figure 5 shows that quartz is the dominant mineral in the sand sample, and is one of the common minerals on the earth's crust.

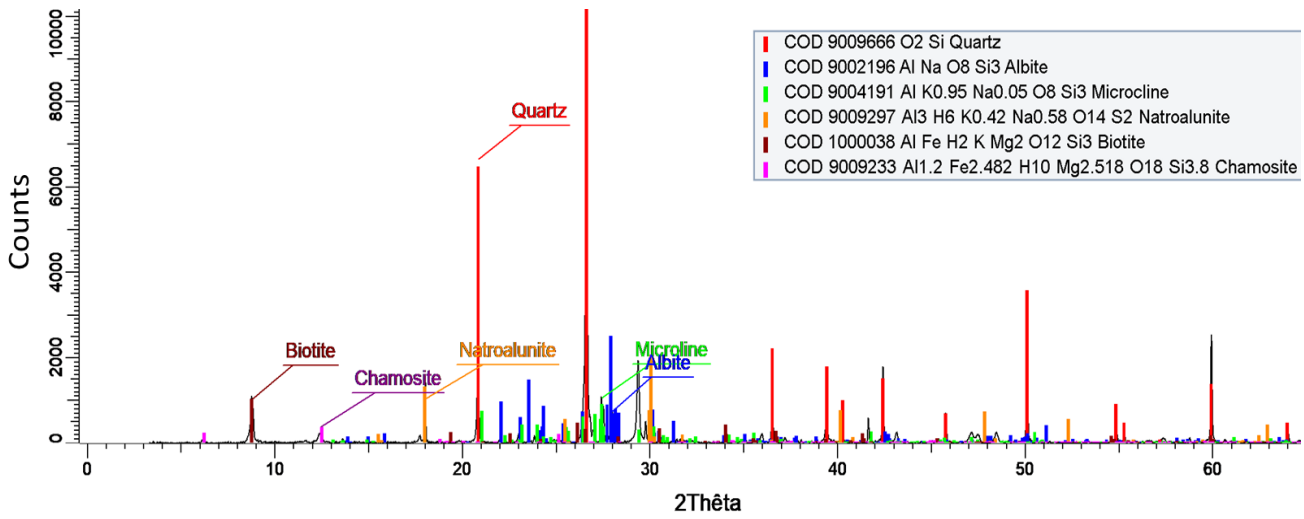

Figure 5. XRD analysis of recycled sand samples.

The proportion of different minerals from the XRD analysis in recycled sand is shown in Table 4.

Table 4. Mineralogical composition of sand.

Mineralogy	Quartz	Albite	Microcline	Natroalunite	Biotite	Chamosite
Concentration (%)	43.3	26.5	12.8	10	5.4	2

Table 4 shows that common minerals in recycled sand are quartz, feldspar (albite), microcline, natroalunite, biotite and chamosite. The low percentage of clay minerals in Table 4 is due to the constituents of concrete, as concrete usually has very low clay.

3.2. Characteristics of Binders

Rolac optimum, GGBS slag (Ecocem) and ECOSOIL® binders were used to stabilize recycled sand. The Rolac binder is mainly composed of clinker. Another important constituent is lime. GGBS and ECOSOIL® binder is composed of slags with similar compositions. Table 5 shows the composition of different binders.

Table 5. Composition and characteristics of binders.

Rolac		**GGBS**		**ECOSOIL®**	
Clinker	80%	Slags	95 ± 5%	LHF	30%
Lime	8%	Clinker	5 ± 3%	LLD	65%
Secondary constituents	5%	pH	9.8	Regulator	5%
CaO	65%	CaO	40%	-	-
SiO_2	20.8%	SiO_2	35%	-	-
Al_2O_3	5.4%	Al_2O_3	10%	-	-
Fe_2O_3	2.2%	MgO	8%	-	-
Rc-7	44.9 MPa	Rc-7 days	31 MPa	Rc-7 days	21.7 MPa
Density (g/cm^3)		-		-	2.7

Note: Rc-7 days = compressive strength after 7 days, mixture of blast furnace slag (LHF) and steelworks slag (LLD).

Table 5 shows that clinker and lime are the major constituents of the Rolac binder. Its compressive strength after 7 days of air drying is around 44.9 MPa. GGBS slag is another binder that is composed of ground-granulated blast slag. The composition of GGBS binder in Table 5 shows that calcium oxide, silica, alumina and magnesium oxide are major components of GGBS slag-based binder. In the case of sulphate-rich soil, GGBS binders show good strength, as the swelling of soils takes place in case of a stabilization with cement [26]. Table 5 shows that the ECOSOIL® binder is also composed of mainly slags with the addition of a 5% regulator.

3.3. Unconfined Compressive Strength of Samples

The unconfined compressive strength of cylindrical specimens was determined to investigate the strength of cylindrical specimens and the effect of the addition of binders. Compressive stress–strain curves of recycled sand with Rolac binders are shown in Figure 6.

Figure 6 shows that from S0 to R5, binder addition sand specimens show a plastic deformation along with a similar modulus of elasticity and low strength. The plastic deformation under compressive load is due to the presence of fine particles and irregular shapes of recycled sand particles from construction and demolition waste. The stress–strain behavior starts to change from R6 to R7, with higher strength and steeper slopes, as the increased bonding of sand grains increases with the higher stabilizer content, thwarting the deformation. In addition, the slow loading rate of the apparatus prevents brittle failure.

Table 6 shows the compressive strength of specimens stabilized with a Rolac binder and GGBS and ECOSOIL® binder.

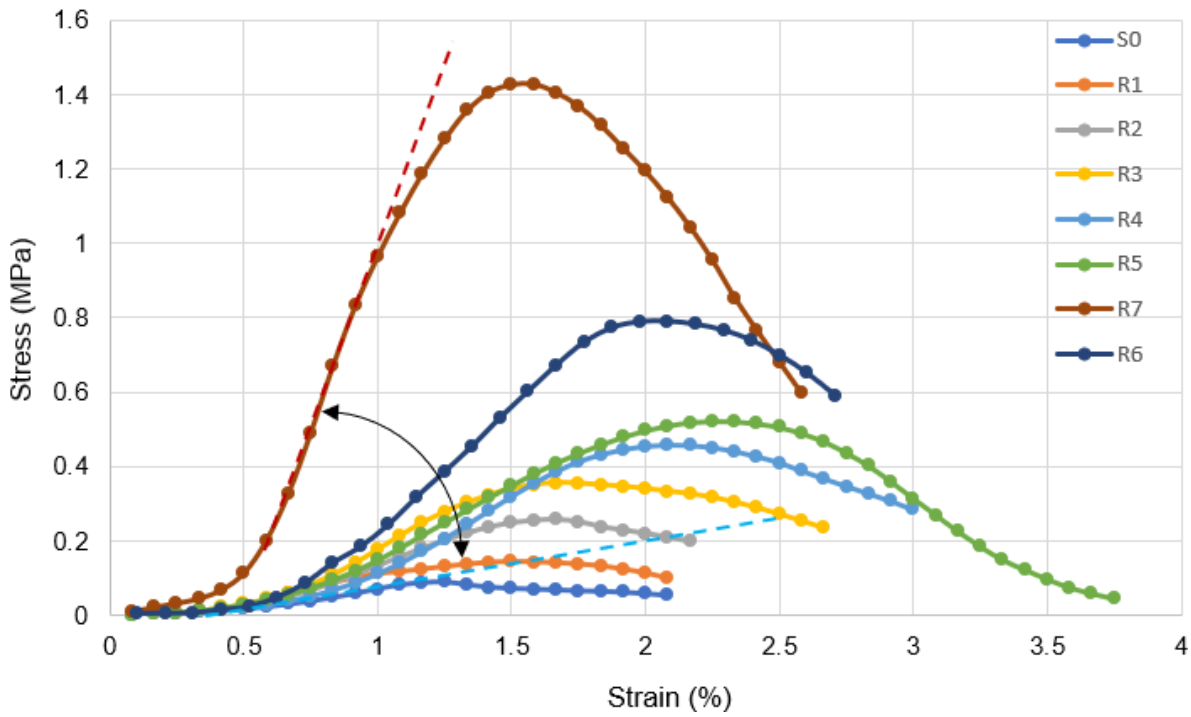

Figure 6. Compressive stress-strain curves of Rolac-sand samples.

Table 6. Compressive strength of stabilized sand specimens.

Rolac	σc (MPa)	GGBS	σc (MPa)	ECOSOIL®	σc (MPa)
S0	0.1	S0	0.1	S0	0.1
R1	0.1	G1	0.2	A1	0.2
R2	0.2	G3	0.3	A3	0.2
R3	0.3	G5	0.3	A5	0.2
R4	0.5	G7	0.5	A7	0.5
R5	0.5				
R6	0.8				
R7	1.2				

Figure 7 shows the average compressive strength of three stabilized recycled sand specimens for each formulation (Rolac, GGBS and ECOSOIL®).

The compressive strength with the addition of a Rolac binder is considerably higher than the specimens manufactured with the addition of ECOSOIL® and GGBS slag, and it is 12 times higher than non-stabilized soil with a 7% addition of Rolac. The reactivity of the sand–binder mixture is low until a 5% Rolac addition and, afterwards, increases significantly. The clinker is mainly composed of carbonates and clay minerals; its hydration forms calcium silicate hydrates (CSSH) and calcium aluminate hydrates (CAH), along with the release of calcium hydro oxide (CaOH). The hydration of Rolac hardens the sand mixture and increases its strength. The reactivity of the binder continues with unreactive cement particles and free water and modifies the soil's strength and durability [41,42].

It can be observed from Figure 7 that the UCS strength of specimens stabilized with the Rolac binder is 1.2 MPa with a 7% binder addition. It is significantly greater than 1 MPa of strength, which is the minimum strength required for the foundation layer and subbase for roads according to French standards. The compressive strength of sand specimens increases with the addition of the GGBS and Ecosoil binder. The strength increase is gradual and relatively low. At a 7% addition of the GGBS and Ecosoil binder, the strength of stabilized sand specimens is five times higher than non-stabilized samples. The strength increase in

sand specimens is due to the formation of cementitious compounds with the hydration of GGBS and ECOSOIL binders with the reaction of pozzolana in slag and calcium hydroxide in sand. In addition, slag components fill the voids in sand and decrease the quantity of free, fine fractions [43]. However, the low strength with GGBS and ECOSOIL® binders is due to the absence of a strong activator and lower molding moisture content. The alkali activator of slags (the GGBS and ecosoil binder) helps to generate the CASH structure which increases the bonding [28].

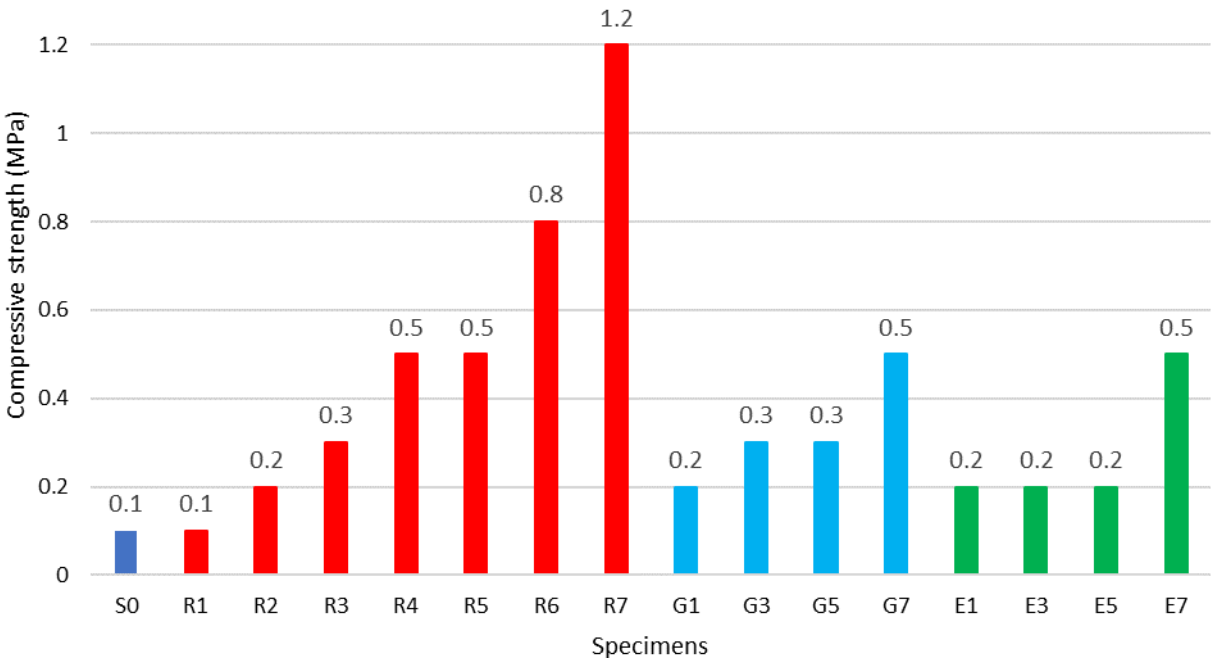

Figure 7. Compressive strength of stabilized recycled sand specimens. Note: S0 = control specimen with 100% sand, R1 = sample with 1% Rolac addition, G1 = sample with 1% GGBS and E1 = sample with 1% ECOSOIL®.

Furthermore, the stabilization with GGBS is a slow process that takes time. The performance of ECOSOIL® is also considerably lower and similar to GGBS, which is comprehensible because both have a similar composition, as ECOSOIL® is also mainly composed of slags. The compressive strength, initial deformation modulus and deformation at the failure of sand specimens, stabilized with the addition of different percentages of binders, are shown in Table 7.

Table 7. Mechanical parameters of recycled sand specimens.

Sample	S0	R1	R2	R3	R4	R5	R6	R7	E1	E3	E5	E7	G1	G3	G5	G7
σc (MPa)	0.1	0.1	0.2	0.3	0.5	0.5	0.8	1.2	0.2	0.2	0.2	0.5	0.2	0.3	0.3	0.5
E (MPa)	0.1	0.2	0.2	0.4	0.38	0.3	0.64	1.3	0.2	0.5	0.2	0.5	0.2	0.3	0.2	0.2
ε (%)	1.7	1.6	1.8	1.8	2.0	2.0	2.1	2.2	0.3	0.7	1.6	1.3	1.7	1.8	1.9	1.9

Note: σc = compressive strength, E = initial deformation modulus and ε = deformation at failure.

Table 7 shows that the compressive strength is at its maximum with a 7% addition of the Rolac binder and meets the strength requirement, thus providing an opportunity to locally develop sustainable and cost-effective construction material. Initially, the tangent modulus increases with the increasing compressive strength of specimens. The deformation of most of the specimens is between 1.6 to 2% at peak load.

Similar studies have been conducted on dredged sediments, excavated soils and quarry sands. Shalabi et al. [20] stabilized quarry sand with the addition of up to 8% cement. After a curing time of 28 days with an 8% cement addition, a compressive strength of 4.5 MPa is

achieved, which is sufficient to meet the strength requirement for the subbase layer of roads. Hussan et al. [28] stabilized highly organic dredged sediments by using a conventional binder and alkali-activated ground-granulated blast furnace slag. It was observed that with the 20% addition of GGBS, a compressive strength of 7.6 MPa is achieved after 28 days which fulfills the strength requirement for sediment reuse in the subbase and foundation layer of roads. For the use of natural soil in the subbase layer of roads, the addition of sand can improve the engineering characteristics of soil. Roy [44] found that the addition of 15% sand with natural soil increases the bearing capacity of soil significantly and makes it suitable for road applications.

4. Conclusions

In this study, physico-chemical and mineralogical characteristics of recycled sand from Rennes, France were determined for its reuse in pedestrian pathways. The grain size analysis of sand shows that the percentage of fine particles of size below 0.063 mm is 2.8%. The classification of recycled sand shows that this material is D2 soils, which are non-sensitive to water and suitable for road and pathway applications. Chemical analysis of sand shows that the percentage of soluble sulfate is 0.51% which is lower than the maximum authorized limit of 1.3% in French standards for road applications. The methylene blue value of sand is 0.05 g/100 g, which shows that sand is insensitive to water. The characterization of sand was followed by the fabrication of sand specimens with dynamic compaction. The testing of sand specimens shows that non-stabilized recycled sand specimens have a compressive strength of 0.1 MPa, which is significantly low. Sand samples were stabilized with 0 to 7% of the Rolac, GGBS and ECOSOIL® binder addition. The maximum compressive strength of stabilized sand samples is achieved at a 7% addition of binder which is 1.2 MPa for the Rolac addition and 0.5 MPa for GGBS and ECOSOIL® binders. Recycled sand with 7% Rolac binder has a strength higher than 1 MPa and meets the compressive strength requirements for its reuse in road applications.

This investigation highlights the possibility for the reuse of recycled sand for pathways and road applications. The reuse of recycled sand can be a sustainable and eco-friendly solution to replace the quarry sand. However, further testing is recommended to observe the tensile strength and durability of recycled sand specimens for its use in road applications with low traffic and for pedestrian pathways.

Author Contributions: Conceptualization, A.K., A.P. and A.M.; Experimental work, M.H. and D.L.; Analysis, M.H., A.K., H.Z. and D.L.; Writing, M.H., A.K. and D.L.; Supervision, A.K., A.M., A.P., N.L. and H.Z., Review and editing, M.H., A.K., H.Z., D.L. and P.A.H.R.; Project administration, A.K., A.M., A.P., N.L. and H.Z.; Funding acquisition, A.K., A.M. and A.P. All authors have read and agreed to the published version of the manuscript.

Funding: This work has been funded by the project European Union, NextGenerationEU under the France Relance program for the valorization of inert excavated soils (VALODEB) with the collaboration of Unilasalle Rennes and Gendrot TP.

Data Availability Statement: Data are contained within the article.

Acknowledgments: We are thankful to Jean Baptiste Besnier, Ivane Lelievre, Elise Chenot, Sebestian Potel and Clarisse Roig for their technical assistance and cooperation in the experimental work.

Conflicts of Interest: Author Antony Provost was employed by the company GENDROT TP. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

1. French Ministry of Ecology. *Observation and Statistics Service (SOeS) of the Ministry of Ecology, Sustainable Development and Energy*; Review of the production of waste in France; French Ministry of Ecology: Paris, France, 2015.
2. Behera, M.; Bhattacharyya, S.K.; Minocha, A.K.; Deoliya, R.; Maiti, S. Recycled aggregate from CDW waste & its use in concrete—A breakthrough towards sustainability in construction sector: A review. *Constr. Build. Mater.* **2014**, *68*, 501–516. [CrossRef]

3. CESER. Avis du CESER sur le Dossier du Conseil Régional 'Modification n°1 du Schéma Régional D'aménagement, de Développement Durable et D'égalité des Territoires'. Conseil Economique, Social et Environmental Régional. 2023. Available online: https://www.bretagne.bzh/app/uploads/sites/8/2023/06/Avis-du-CESER-sur-la-Modification-SRADDET-session-19-et-20-juin-2023.pdf (accessed on 5 November 2023).
4. FFB. Déchets de Chantier: C'est Qoui la REP Bâtiment? French Building Federation. 2023. Available online: https://www.ffbatiment.fr/gestion-entreprise/organiser-mon-chantier/dechets-de-chantier-bonnes-pratiques-environnementales/dossier/dechets-de-chantier-c-est-quoi-la-rep-batiment (accessed on 5 November 2023).
5. Aliaoui, F.; Belkadi, A. Etude de L'influence du Type des Granulats Recyclés sur le Comportement du Béton de Sable. Master's Thesis, Université Yahia Fares de Medea, Médéa, Algeria, 2021; 102p. Available online: http://dspace.univ-medea.dz:8080/handle/123456789/805 (accessed on 25 October 2023).
6. UNPG. Module D'information Environnementale de la Production de Granulats Recyclés. Union Nationale DES Producteurs de Granulats. 2017. Available online: www.unpg-mie-production-granulats-recycles-2017-1.pdf (accessed on 6 November 2023).
7. Ben Fraj, A. Le Recyclage du Béton dans le Béton: Apport de la Recherche. Conférence Technique Territoriale, Sobriété, Frugalité et Réemploi. Metz, France. 2023. Available online: https://www.cerema.fr/system/files/documents/2023/02/5._presentation_beton_recycle_dima.pdf (accessed on 13 November 2023).
8. Economic Unit of Brittany. Le Recyclage des Déchets du BTP en Bretagne: Quantification et Pratiques. 2021. Available online: https://www.bretagne.developpement-durable.gouv.fr/IMG/pdf/202112_rapport_recyclage_dechetsbtp_bzh.pdf (accessed on 6 November 2023).
9. Angulo, S.C.; Ulsen, C.; John, V.M.; Kahn, H.; Cincotto, M.A. Chemical–mineralogical characterization of CDW waste recycled aggregates from São Paulo, Brazil. *Waste Manag.* **2009**, *29*, 721–730. [CrossRef] [PubMed]
10. Silva, R.V.; Brito, J.; Dhir, R. Properties and composition of recycled aggregates from construction and demolition waste suitable for concrete production. *Constr. Build. Mater.* **2014**, *65*, 201–217. [CrossRef]
11. Arabi, N.; Berredjem, L. Valorisation des déchets de démolition comme granulats pour bétons. *Environ. Ingénierie Dév.* **2021**, *60*, 25–30. [CrossRef]
12. Sampaio, H.C.; Cazacliu, B.G.; Ambrós, W.M.; Kronbauer, M.A.; Tubino, R.M.C.; Dal Molin, D.C.C.; Oliva Moncunill, J.; Miltzarek, G.L.; Waskow, R.P.; dos Santos, V.L.G.; et al. Characterization of demolished concretes with three different strengths for recycling as coarse aggregate. *Minerals* **2021**, *11*, 803. [CrossRef]
13. *AFNOR NF EN 206+A2/CN*; Béton—Spécification, Performance, Production et Conformité—Complément National à la Norme NF EN 206+A2. AFNOR: Saint-Denis, France, 2022.
14. Andrzejuk, W.; Barnat-Hunek, D.; Góra, J. Physical properties of mineral and recycled aggregates used to mineral-asphalt mixtures. *Materials* **2019**, *12*, 3437. [CrossRef] [PubMed]
15. Maimouni, H. Suivi des Echanges d'eau Dans un Mortier de Sable Recyclé Modèle à L'état Frais par une Approche Rhéologique. Ph.D. Thesis, École Centrale de Nantes, Nantes, France, 2018.
16. Movahed, S.; Azad, S.P.; Zakeri, H. A safe pedestrian walkway; Creation of a safe public space based on pedestrian safety. *Procedia—Soc. Behav. Sci.* **2012**, *35*, 572–585. [CrossRef]
17. Moretti, L.; Di Mascio, P.; Fusco, C. Porous concrete for pedestrian pavements. *Water* **2019**, *11*, 2105. [CrossRef]
18. Buchser, M. Revêtements de sol. Bureau de Prévention des Accidents. Berne. 2014. Available online: https://www.batidoc.ch/m10/85/41132285/etc/43/42087643.pdf (accessed on 8 November 2023).
19. SMAEG. Guide de la Définition et des Bons Usages des Materiaux de Revetement et du Petit Mobilier Urbain Relatifs à L'espace public. Syndicat Mixte d'Action pour l'Expansion de la Gâtine. 2011. Available online: http://www.intragatine.org/paysgatine/portail2/ressources/guide-materiaux/materiaux-revetement/02-les_sols_stabilises-guide_materiaux_pays_gatine_2011.pdf (accessed on 5 November 2023).
20. Shalabi, F.I.; Mazher, J.; Khan, K.; Alsuliman, M.; Almustafa, I.; Mahmoud, W.; Alomran, N. Cement-Stabilized Waste Sand as Sustainable Construction Materials for Foundations and Highway Roads. *Materials* **2019**, *12*, 600. [CrossRef] [PubMed]
21. Afrin, H. A Review on Different Types Soil Stabilization Techniques. *Int. J. Transp. Eng. Technol.* **2017**, *3*, 19–24. [CrossRef]
22. *AFNOR NF EN 933-1*; Essais Pour Déterminer les Caractéristiques Géométriques des Granulats—Partie 1: Détermination de la Granularité—Analyse Granulométrique par Tamisage. AFNOR: Saint-Denis, France, 2012.
23. *AFNOR NF EN 1097-6*; Essais pour Déterminer les Caractéristiques Mécaniques et Physiques des Granulats—Partie 5: Détermination de la Teneur en eau par Séchage en Etuve Ventilée. AFNOR: Saint-Denis, France, 2008.
24. *AFNOR NF P94-093*; Sols: Reconnaissance et Essais—Détermination des Références de Compactage d'un Matériau—Essai Proctor Normal—Essai Proctor Modifié. AFNOR: Saint-Denis, France, 2021.
25. *AFNOR NF EN 1744-1*; Essais Pour Déterminer les Propriétés Chimiques des Granulats—Partie 1: Analyse Chimique. AFNOR: Saint-Denis, France, 1998.
26. Rabbani, P.; Daghigh, Y.; Atrechian, M.A.; Karimi, M.; Tolooiyan, A. The potential of lime and grand granulated blast furnace slag (ggbfs) mixture for stabilisation of desert silty sands. *J. Civ. Eng. Res.* **2012**, *2*, 108–119. [CrossRef]
27. METL. *Ministère de l'Equipement, des Transports et du Logement—Assises de Chaussees Guide d'application des Normes pour le Reseau Routier National (French Ministry of Equipment, Transport and Housing—Road Bases Guide to the Application of Standards for the National Road Network)*; Service d'Etudes Techniques des Routes et Autoroutes (Technical Studies Service for Roads and Highways): Bagneux, France, 1998.

28. Hussan, A.; Levacher, D.; Mezazigh, S.; Jardin, L. Valorization of a Highly Organic Sediment: From Conventional Binders to a Geopolymer Approach. *J. Compos. Sci.* **2022**, *6*, 147. [CrossRef]
29. Ciments Calcia. Stabex, Esthétique et Performance des sols Stabilisés. Stabex. 2008. Available online: www.ciments-calcia.fr (accessed on 11 November 2023).
30. IDRRIM. Acceptabilité Environnementale des Matériaux Alternatifs en Technique Routière, n°32, Institut Des Routes, des Rues et des Infrastructures pour la Mobilité. 2017. 17p. Available online: https://www.idrrim.com/ressources/documents/9/5044-NOTE-D-INFORMATION-N-32_VF.pdf (accessed on 29 October 2023).
31. Cazacliu, B.; Cothenet, A. *Etude de Faisabilité et Financière d'une Création de Plate-Forme de Valorisation de Déblais et Gravats du BTP*; Internal Project Report; Gendrot TP Company: Rennes, France, 2021; 38p.
32. McNeil, K.; Kang, T.H.K. Recycled Concrete Aggregates: A Review. *Int. J. Concr. Struct. Mater.* **2013**, *7*, 61–69. [CrossRef]
33. *AFNOR NF P 11-300*; Exécution des Terrassements—Classification des Matériaux Utilisables dans la Construction des Remblais et des Couches de Forme d'Infrastructures Routières. AFNOR: Saint-Denis, France, 1992.
34. *AFNOR NF P18-545*; Éléments de Définition, Conformité et Codification. AFNOR: Saint-Denis, France, 2021.
35. GTR. *Guide des Terrassements Routiers, Réalisation de Remblais et des Couches de Formes, Fascicules I et II, GTR SETRA-LCPC*, 2nd ed.; IDRRIM: Paris France, 2000; 240p, ISBN 2-7208-3810-1.
36. Daman, K.P. Supplementary cementing materials. In *Developments in the Formulation and Reinforcement of Concrete*, 2nd ed.; Woodhead Publishing Series in Civil and Structural Engineering; Woodhead Publishing: Sawston, UK, 2019; pp. 55–85. [CrossRef]
37. Makusa, G.P. Soil Stabilization Methods and Materials in Engineering Practice: State of the Art Review. Ph.D. Thesis, Luleå University of Technology, Luleå, Sweden, 2012; 38p. Available online: https://www.diva-portal.org/smash/get/diva2:997144/FULLTEXT01.pdf (accessed on 10 November 2023).
38. Moreno-Pérez, E.; Hernández-Ávila, J.; Rangel-Martínez, Y.; Cerecedo-Sáenz, E.; Flores AReyes-Valderrama, M.I.; Salinas-Rodríguez, E. Characterization and possible uses of recycled aggregates from construcction and demolition waste from Mexico City. *Minerals* **2018**, *8*, 237. [CrossRef]
39. Ulsen, C.; Antoniassi, J.L.; Martins, I.M.; Kahn, H. High quality recycled sand from mixed CDW is that possible? *J. Mater. Res. Technol.* **2021**, *12*, 29–42. [CrossRef]
40. Bouakba, H.; Rezzak, A. L'étude de Stabilisation de sol par L'ajout de Ciment et de Fibre Naturelles. Master's Thesis, Université de Jijel, Jijel, Algeria, 2016; 114p. Available online: http://dspace.univ-jijel.dz:8080/xmlui/handle/123456789/7252 (accessed on 8 November 2023).
41. Firoozi, A.A.; Olgun, C.G.; Firoozi, A.A.; Baghini, M.S. Fundamentals of soil stabilization. *Int. J. Geo-Eng.* **2017**, *8*, 26. [CrossRef]
42. Saussaye, L. Traitement des Sols Aux Liants Hydrauliques: Aspects Géotechniques et Physicochimiques des Perturbations de la Solidification. Ph.D. Thesis, Université de Caen, Caen, France, 2012.
43. Yadu, L.; Tripathi, R.K. Effects of granulated blast furnace slag in the engineering behavior of stabilized soft soils. *Procedia Eng.* **2013**, *51*, 125–131. [CrossRef]
44. Roy, T.K. Influence of sand on strength characteristics of cohesive Soil for using as Subgrade of road. *Procedia—Soc. Behav. Sci.* **2013**, *104*, 218–224. [CrossRef]

Disclaimer/Publisher's Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.