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Valorization of Dredged Sediments and Recycled Concrete Aggregates in Road Subgrade Construction

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Abstract: Large quantities of dredged sediments and recycled concrete materials are generated every year all over the world. The disposal of these large quantities in landfills represents serious environmental problems. Furthermore, high-quality raw materials for construction are depleting, and their use cannot be sustained. The valorization of dredged sediments and recycled concrete materials as alternative construction materials has the potential to reduce the impact of these two issues. In this context, this study aims at investigating the feasibility of using dredged sediments and recycled concrete aggregates as alternative raw material for road subgrade construction. Various mix designs were prepared using dredged sediments and recycled concrete aggregates. The mixes were then treated with quicklime and road binder as specified in the French soil treatment guide. Their physical, mechanical, and geotechnical properties confirmed the feasibility of using recycled concrete aggregates and dredged sediments up to a certain percentage in road subgrade construction. Moreover, they showed that the mixes containing 20% of dredged sediments met road subgrade minimum physical and mechanical properties, such as immediate bearing capacity, unconfined compression strength, indirect tensile strength greater, and UCSI/UCS60 ratio. Finally, leaching tests were conducted to ensure the environmental safety of the various mixes. The results showed that the mixes met the thresholds for their use in road subgrade construction. The feasibility of using dredged sediments and recycled concrete aggregates in foundations and base layers will be studied in future projects.

Keywords: sediment; recycled concrete aggregate; road construction; eco-friendly

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1. Introduction

Today, the environmental issues related to the management of natural resources are currently considered as major and high priority in nature (COP). The need to find alternative solutions, particularly by implementing circular economy concepts and adopting new economic models, is more than necessary. In this perspective, the substitution of natural materials by alternative materials presents itself as an interesting solution vis à vis this socio-economic and environmental challenge, which is fully in line with a sustainable development and circular economy approach.

The construction industry consumes more than 453 million tons of granular materials per year in France (UNPG, 2019). More than half of that quantity is consumed in road construction. This situation may lead to severe depletion and scarcity of natural construction materials in France, which would make them not sustainable. Thus, there is a pressing need for finding new alternative construction materials, especially for road projects. On the other hand, significant quantities of concrete waste and dredged sediments are produced every year, whose disposal is becoming more and more complicated. In France, about

50 million m^3 of dredged sediments are collected each year, mostly from estuarine maritime ports (90%) to ensure their good functioning by preventing their silting [1].

Several regulations govern sediment management both nationally and internationally. When they cannot be dumped in the sea, the sediments are managed on land as waste. In this context, waste management generates environmental, technical and economic issues.

During the last decade, several research studies have been conducted on the valorization of dredged sediments as alternative aggregates in road construction [2–7]. However, the results of these studies have shown that the use of dredged sediments alone as alternative aggregates did not yield satisfactory road performance. The studies indicated that the performance of the road could be improved by adding a granular corrector [8,9] to the dredged sediment mixtures to improve the compactness of the granular skeleton in the form of natural sand or by using a stabilization/solidification process involving hydraulic binder and lime [10–13] to improve the geotechnical properties and mechanical behavior of the sediments. On the other hand, the construction industry produces large quantities of construction and deconstruction waste (CDW), which is mainly composed of concrete. The disposal of these huge quantities of CDWs poses a storage problem because of saturated landfills and an environmental one due to their transportation-extensive pollution. Most CDWs are characterized by their low environmental impact due to their physical and chemical characteristics. The Waste Framework Directive (2008) provided the measures to: (1) prevent the harmful effects of CDW generation and management on the environment and human health and (2) improve resource use efficiency. These measures are essential for a transition to a circular economy [14]. The directive set a target of 70% for recycled CDW by 2020. The studies, which were conducted to achieve this target, showed that CDW can be used as: (1) aggregate in concrete [15–19], backfill, road construction, (2) as cement to produce clinker [20–22], or (3) as mineral addition for cementitious material [23–27]. In France, recycled concrete aggregates (RCA) have a specific classification, in which GD0 and GD1 classes are assimilated into soils with a diameter Dmax less than 150 and 80 mm, respectively. During the manufacture of RCAs, the cement paste of the original concrete adheres to the natural aggregate, giving it high water absorption [28–30], which leads to an increase in the optimum water content and a decrease in the maximum dry density [31].

Dredged sediments and soil-assimilated RCAs are currently used separately according to the French GTR guide [32] but have never been used together. In the various works, sediments are used with sand as a granular corrector, which is a non-renewable resource that is rarely found near construction sites. The aim of this study is to use RCAs as a granular corrector for sediments. RCAs are materials that are easily found locally [33] and represent a large part of waste from the construction industry.

The objective of this paper is to study the feasibility of using both dredged sediments and RCAs in pavement subgrade materials. This objective is in line with the valorization of waste to make secondary raw materials for the construction sector and to promote the use of local materials as well. Several mixes with different percentages of dredged sediments and RCA were selected and optimized using the Talbot–Fuller–Thompson spindle, in order to meet the normative requirements for road materials. The geotechnical, physical, and mechanical properties of the prepared mixes were obtained through testing and were analyzed. The immediate bearing ratio and treatment suitability tests were also carried out to check the suitability of using these mixes in subgrade construction. Finally, an environmental characterization was carried out to validate the environmental suitability of the mixes for subgrade construction.

2. Materials and Methods

2.1. Marine Dredged Sediments (SED)

The marine sediments (Figure 1) were dredged from the Arcachon basin in France. The accumulation of sediments in the basin has hampered both commercial and pleasure navigation. The material is extracted where it is placed in settling ponds. The sediments were collected from different parts of the basin. They were deagglomerated, sieved to 4 mm and then homogenized.

Figure 1. Illustration of raw materials (in **left**) and sediment (in **right**) RCA.

2.2. Recycled Concrete Aggregate (RCA)

The RCAs (Figure 1) were collected from a building deconstruction in the north of France. They were recycled gravels with initial and final granulometries of 0/20 and 0/5 mm, respectively, after sifting. The fine content of RCAs was determined by: (1) wet sieving on a 63 µm sieve and (2) analysis using laser granulometer Beckman Coulter LS 13 320 analyzer based on EN ISO 13320 standard [34]. The particle size distribution was obtained using various sieves between 63 µm and 8 mm, according to XP 94-041 standard [35].

The RCAs are classified as GD1 and composed mainly of concrete product. The choice of using GD1 aggregates allows us to use them according to the GTR and to apply the same identification parameters as for a natural soil for use in road subgrade.

2.3. Material Characterization

2.3.1. Physical Characterization

The physical characteristics of SEDs and RCAs are summarized in Table 1.

Table 1. SED and RCA physical characteristics.

Parameter	Units	SEDs	RCAs	Testing Standard
MBV (g/100 g)	g/100 g	1.52	0.17	NF P94-068
Organic matter content	%	7.35	3.49	XP P94-047
Absolute density	g/cm^3	2.54	2.55	NF EN 1097-7
Initial water content	%	38.0	4.78	NF P 94-050
Particle size distribution				EN ISO 13320
Sand fraction (% > 63µm)	%	59.9	85.9	
Silt fraction (2 µm < % < 63 µm)	%	35.0	12.8	
Clay fraction (% < 2 µm)	%	5.07	1.37	
Atterberg limit				NF P94-051
Liquid limit	%	37.0	-	
Plastic limit	%	17.0	-	
Plasticity index	%	20.0	-	

The material organic matter contents were determined according to the XP P94-047 [36] standard.

The methylene blue values were determined for each material in each mix according to NF P94-068 standard.

The raw material Atterberg limits were determined according to the standard NF EN ISO 17892-12 [37].

The material particle densities were determined using a Micromeritics ACCUPYC 1330 helium pycnometer according to standard NF EN 1097-7 [38].

The initial water contents for SEDs and RCAs were equal to 38% and 4.78%, respectively. The absolute densities for SEDs and RCAs were equal to 2.54 and 2.55 g/cm^3, respectively.

The limits of liquidity and plasticity of SEDs were equal to 37% and 17%, respectively. The plasticity index of SEDs was equal to 20%, which shows that SEDs are moderately argillaceous. This finding was confirmed by a clay fraction value of 5.07% and a methylene blue value (MBV) indicating higher plasticity and water sensitivity for SEDs. The RCAs were sandy, exhibiting a sandy fraction of 85.86% and water insensitivity with an MBV value of 0.17 g/100 g.

2.3.2. Mineralogical Characterization

Figure 2 shows XRD patterns for SEDs and RCAs. The peaks observed in the XRD patterns for RCAs are an indication for a high content of quartz and calcite. The quartz and calcite originate from recycled concrete silica sand and portlandite carbonation, respectively. The results do not suggest the presence of portlandite, which is a strong indication of RCA carbonation. The observed small peaks correspond to albite, which is a feldspar family mineral present in natural aggregates. The sediments are mainly composed of quartz and illite.

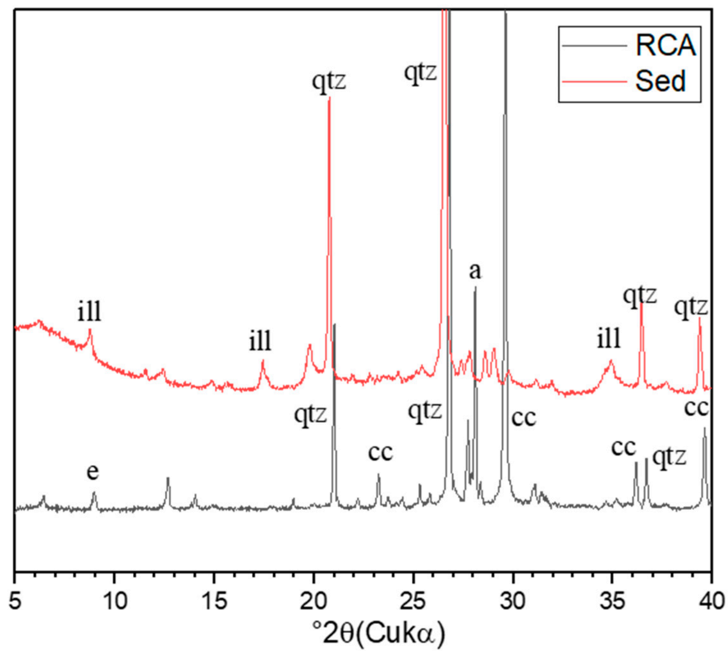

Figure 2. XRD patterns of RCAs and SEDs; qtz, quartz; cc, calcite; e, ettringite; a, albite; ill, illite.

2.3.3. Hydraulic Binder and Quicklime

The Eqiom hydraulic road binder VDS was composed of 50% clinker, 40% blast furnace slag, and 10% secondary constituents. A commercial quicklime, which included 2% by weight calcium hydroxide ($Ca(OH)_2$) and 1.5% by weight calcite ($CaCO_3$), was used in the study.

2.4. Methods

2.4.1. Mix Design

The mix optimization was performed using the Talbot–Fuller–Thompson spindle semi-empirical method, which allowed us to determine the proportion of sediment (S) and

RCAs (G) to create a granular skeleton with minimum voids and maximum compactness. The spindle was obtained using Equation (1) [8]:

$$P = \left[\frac{d}{D}\right]^{n} \times 100 \tag{1}$$

where D (mm) = aggregate maximum diameter, d = sieve size (mm), P (%) = particle percent passing (%) based on sieve size d, and n = empirical constant (fitting coefficient) whose value is between 0.25 and 0.45.

The RCAs are quite well scaled and fit perfectly in the spindle. On the other hand, the sediments are quite far from the spindle with a rather fine grain size. The addition of RCAs to the sediment improves the particle size distribution of the mixture.

Figure 3 shows that the more sediments were added, the further the mix grain size distribution was away from the optimal spindle. The four mixes selected for the study were: (1) 20% of sediment and 80% of RCA (20S80G), (2) 30% of sediment and 70% of RCA (30S70G), (3) 50% of sediment and 50% of RCA (50S50G), and 100% of sediment (100S).

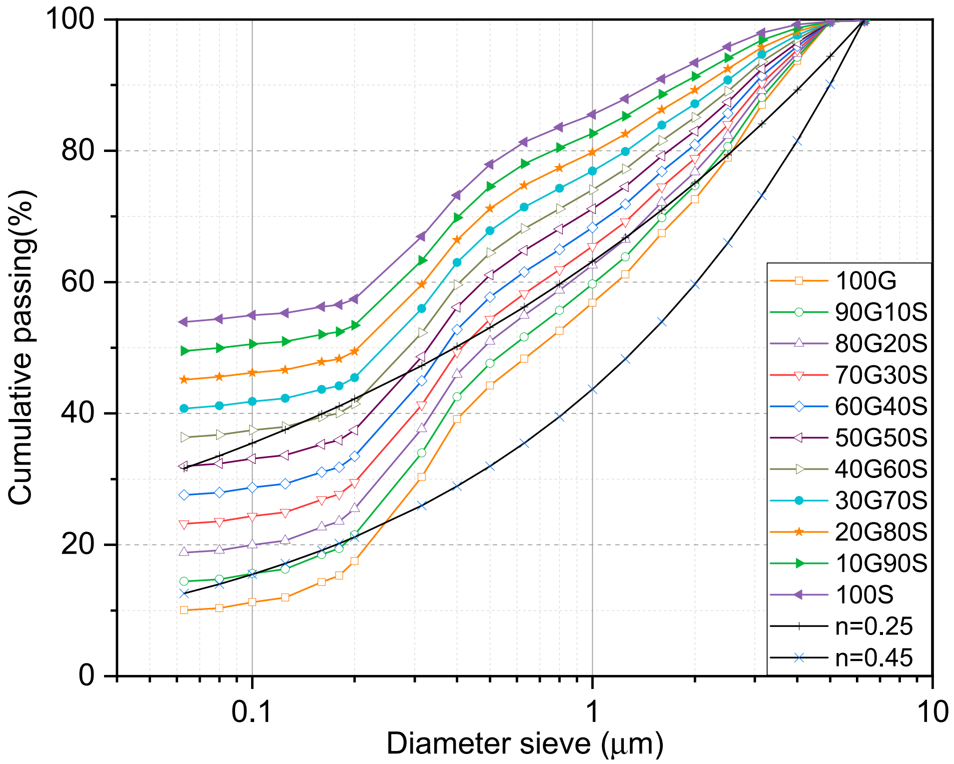

Figure 3. Mix grain size distribution and optimal reference curves.

2.4.2. Geotechnical Classification

The GTR French technical guide [32] and the standard NF P 11-300 [39] were strictly followed in determining the classification of soils used in backfill and subgrade. They address mix grading, methylene blue value, organic matter content, and Atterberg limits.

2.4.3. Normal Proctor Test and Immediate Bearing Ratio

The normal proctor test and the immediate bearing ratio were determined based on the standards NF EN 13286-47 [40], NF EN 13286-2 [41], and NF P94-093 [42] to evaluate if the selected mixes can be used in subgrade construction. The tests were conducted using a mold with a diameter of 15 cm and a height of 12 cm. The mixes were compacted in three equal layers with 56 strokes for each layer with a drop height of 305 mm. Then, three samples were taken from the compacted soils to determine the optimal water content and dry density.

2.4.4. Mechanical Behavior

The long-term mechanical properties (i.e., average value for three specimens) were determined after 7, 28, 60, and 90 days of curing using an Instron 5500R electromechanical press. They were determined at the optimal content, which was obtained using the proctor test. The specimens used to determine the compressive and indirect tensile strengths were set equal to 98.5% and 96% of the optimal dry density, respectively. The specimens were prepared using a static compression test based on standard NF EN 13286-53 [43].

Unconfined Compression Strength (UCS)

The compressive strengths were determined using cylindrical specimens with a diameter of 5 cm and a height of 10 cm. The load was applied continuously and uniformly to failure according to NF EN 13286-41 [44].

Indirect Tensile Strength (ITS)

The indirect tensile strength was determined using specimens with a height and a diameter of 5 cm with a uniform stress not exceeding 0.2 MPa per second according to the standard NF EN 13286-42 [45].

Modulus of Elasticity

The elastic modulus was determined using cylindrical specimens with a diameter of 5 cm and a height of 10 cm according to the standards NF EN 13286-41 [44] and NF EN 13286-43 [46]. The elastic modulus was calculated using Equation (2):

$$E = 1.2 \times \frac{Fr}{\pi \times D^2 \times \varepsilon} \tag{2}$$

with E = elastic modulus (MPa), Fr = maximum force (Newton), D = specimen diameter (millimeter) and ε = specimen elongation when $F = 0.3 \times Fr$.

2.4.5. Treatment Suitability

According to the standards NF P 94-100 [47] and NF EN 13286-49 [48], the mix suitability is determined by volumetric swelling (VS) and ITS by immersing specimens having a diameter and a height of 5 cm, in water at 40 °C for 7 days. Before immersion, the specimens were kept for 4 h at a temperature of 20 °C and a relative humidity of 90%. The mixes were first treated with quicklime and then with cement. To validate their use in subgrade construction, the mix vs. and ITS values were compared to the thresholds set by the French guide of soil treatment (GTS) [49], which are summarized in Table 2.

Table 2. Treated material sustainability criteria.

	After Conservation in Water at 40 °C for 7 Days	
	VS (%)	**ITS (Mpa)**
Suitable	VS < 5	ITS > 0.2
Doubtful	5 ≤ vs. ≤ 10	0.1 ≤ ITS ≤ 0.2
Unsuitable	VS > 10	ITS < 0.1

2.4.6. Leaching Test

An environmental analysis was performed on raw materials with a water-to-solid ratio of 10 and on various mixes using batch leaching according to the standard NF EN 12457-2 [50]. The concentrations of metallic trace elements (or heavy metals), chlorides, fluorides, and sulfates were determined. The samples were stirred for 24 h in pure water (18.2 MΩ.cm). Then, the solid and liquid fractions were separated using a 15 min decantation. The liquid fraction was filtered through an acetate–cellulose membrane with a pore diameter of 45 µm. The eluate was analyzed using ICP-OES and ion chromatography. In France, the SETRA and CEREMA guides set the leaching thresholds on the use of alternative materials and recycled concrete aggregates for use in road construction. These thresholds are summarized in Table 3.

Table 3. Environmental acceptability criteria for road construction.

	Units	Sediment	RCA	SETRA Guidelines for Alternative Materials	CEREMA Guidelines for RCA
As	mg/kg	<0.1	<0.1	2	0.6
Ba	mg/kg	<0.008	0.19	100	36
Cd	mg/kg	0.13	<0.009	1	0.05
Cr	mg/kg	0.19	0.018	10	4
Cu	mg/kg	0.59	0.067	50	10
Mo	mg/kg	<0.09	<0.09	10	5.6
Ni	mg/kg	2.2	<0.05	10	0.5
Pb	mg/kg	<0.03	<0.03	10	0.6
Sb	mg/kg	<0.06	<0.06	0.7	0.6
Se	mg/kg	<0.08	<0.08	0.5	0.5
Zn	mg/kg	25	<0.01	50	5
Fluoride	mg/kg	3	6	150	60
Chloride	mg/kg	5420	196	15,000	10,000
Sulfate	mg/kg	18,180	3000	20,000	100,000
Soluble fraction	mg/kg	34,670	6110	60,000	

3. Results and Discussion

3.1. Leaching Tests

The eluates after leaching, presented in Table 3, were evaluated according to SETRA [51] and CEREMA [52] guides for road construction materials. The concentrations of trace metal elements, fluoride, chloride, and sulfate were all above the thresholds set for the use of these materials in road construction. It is noted that the concentration of sulfates in sediment leachates is close to the limit threshold for the use of alternative materials in road materials (18,180 mg/kg). This is consistent with the results of previous studies conducted on marine sediments. Maherzi et al. (2018) [13] have highlighted that the presence of sulfates in marine sediments is mainly due to the presence of framboidal pyrite (FeS2), which is found in natural sediments. The presence of chloride in a non-negligible concentration is also noted. This presence of chlorides is due to the origin of the sediments, which are marine sediments.

3.2. Physical and Geotechnical Characterization of Non-Treated and Treated Mixes

The physical characteristics of the mixes are presented in Table 4. The mixes had an MBV lower than 1.5 g/100 g, a percent passing for 80 µm between 19.16% and 32.27%, which classify them as a B5 soil. A similar classification has been found in the literature [8]. The sediments were classified as A1 soil, which corresponds to fine soils and is consistent with the results of other research [3,53,54].

Table 4. Mix physical characteristics and geotechnical classification.

Characteristics	Parameter	Units	20S80G	30S70G	50S50G	100S
Physical	MBV	g/100 g	0.57	0.84	0.98	1.53
	Absolute density	g/cm^3	2.55	2.56	2.57	2.54
	Particle size distribution					
	Grain < 80 µm	%	19.16	23.53	32.37	37.08
	Grain > 2 mm	%	23.23	21.15	16.99	6.6
Geotechnical classification			B5	B5	B5	A1

Figure 4a shows the IBR indexes for non-treated mixes, which reach IPI indexes of less than 20%, ranging between 4.91% and 9.45%. Their dry density optimal water content values were between 1.37 and 1.60 g/cm^3 and between 20.5% and 28.7%, respectively. Thus, it does not allow them to be used as road subgrade.

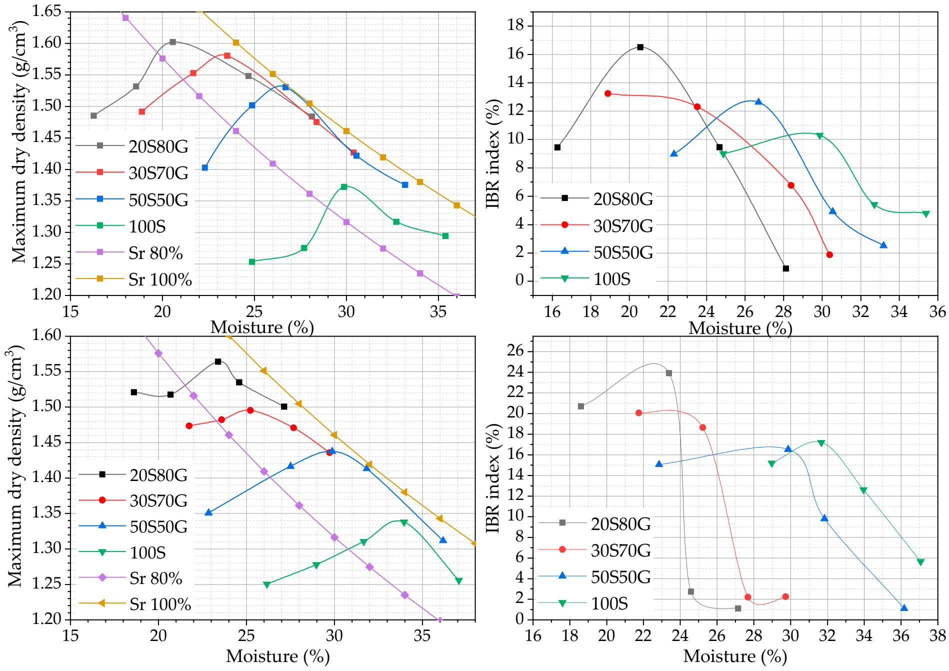

Figure 4. Mix IBR indexes: (**a**) non-treated and (**b**) treated.

There is also a significantly higher optimum moisture content and lower maximum optimum dry density compared to literature works using natural sand [9]. However, the results are similar to other work using RCAs [8].

To improve the geotechnical and mechanical properties of the various mixes, lime and cement treatments were performed as recommended by the GTS for A1 and B5 soils. Table 5 summarizes the results for the studied mixes. All the mixes were treated first with 1% (by mass) quicklime and then with 7% (by mass) cement. The physical characterization showed that the sediments were rich in organic matter. Several studies reported that organic matter can impact the initial lime action on soils (flocculation/agglomeration). Thus, a lime pre-treatment is necessary to make it available for the reactions. The lime fixation point test was performed to determine the percentage of quicklime needed to reach a pH of 12.4 according to XP CEN/TS 17693-1 standard [55] In this study, the sediments were pre-treated with a 3% quicklime prior to their use in the mixes.

Table 5. Designed materials for recycling sediments and granular addition.

	Mixes			
	Sediment (%)	**RCA (%)**	**Quicklime (%)**	**Cement (%)**
20S80G	20	80	1	7
30S70G	30	70	1	7
50S50G	50	50	1	7
100S	100	0	1	7

Figure 4b shows a significant increase in the IBR indexes of treated mixes. The exothermic lime hydration reaction decreased the dry density and increased the optimal water content due to the flocculation of the soil particles in all the mixes. The lime treatment improved the short-term properties of the mixes by improving their IBR values. The 20S80G, 30S70G, 50S50G and 100G mixes move from an IPI of 16.5% to 25.22%, 12.31% to

18.65%, 12.64% to 16.53% and 10.3% to 12.62%, respectively. However, only the treated mix 20S80G had an IBR value of 20%, which is the recommended value for use in subgrade. The more sediment there is, the more the compactness of the mixtures decreases, as shown in Figure 3. Moreover, sediments are composed of a non-negligible part of organic matter, which increases the optimal water content and decreases the maximum dry density but also decreases the compaction characteristics [11].

3.3. Designed Material Sustainability

The treatment suitability test helps to ensure the sought dimensional stability and mechanical behavior in special conditions and in a relatively short time. The objective is to accelerate the hydraulic setting, which occurs in various mixes. Figure 5 shows the ITS and swelling volume of the mixes after immersion in water. The results show that all the mixes satisfied the indirect traction criterion except for mix 100S, which had an ITS value of 0.11 MPa. The swelling volume for all the mixes were below the threshold of 5%. Therefore, all the mixes except 100S are suitable for treatment.

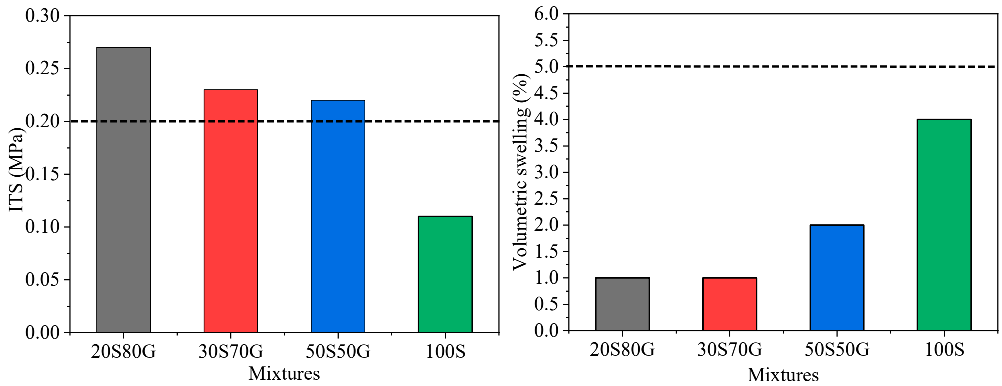

Figure 5. ITS and swelling volume after immersion in water.

All the sample mixes experienced significant swelling volume reduction after treatment. Moreover, the untreated mixes with low and high sediment contents had a low and high swelling volume, respectively. This can be explained by: (1) the sediment organic matter content that favors the swelling and (2) mix insensitivity to water increases with RCA quantity because of the insensitivity of RCAs to water.

3.4. Mechanical Behavior

According to the GTS, the following three requirements have to be verified:

- The circulation on the treated layer is allowed when the UCS reaches a value of 1 MPa.
- The frost resistance is considered satisfactory if the ITS value is higher than 0.25 MPa.
- The resistance to immersion at early age is computed using the ratio between the UCS value after 28 days of curing followed by an immersion during 32 days in water at a temperature of 20 °C (USCI) and the UCS value after 60 days in normal curing at 20 °C (UCS60).
- The mix long-term mechanical behavior is satisfactory when its resistance reaches at most a class of 5.

3.4.1. Trafficability Criteria of Road Sublayers and Frost Resistance

The UCS and ITS values of the various mixes after 7, 28, 60 and 90 days of curing, shown in Figure 6, increase with the curing time for all the mixes. The UCS values show an initial strong increase initially and a stabilization afterward. The mixes 20S80G, 30S70G, and 50S50G reached the circulation age requirement after 7 days, while mix 100S reached it after 28 days.

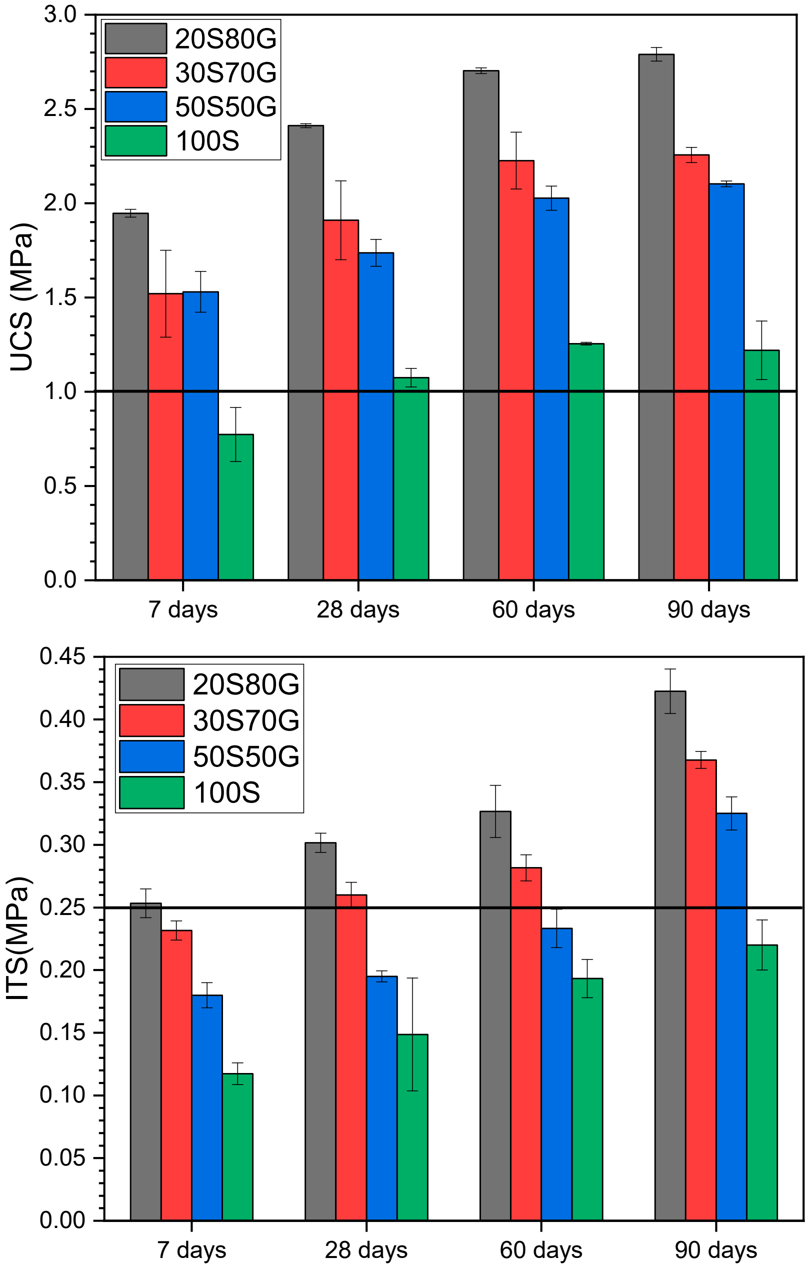

Figure 6. Mix mechanical strength development.

On the other hand, the ITS values continued to increase after 60. The mixes 20S80G, 30S70G, 50S50G reached the criterion of 0.25 MPa after 7, 28, and 60 days, respectively. However, mix 100S did not reach the value of 0.25 MPa.

Decreases in UCS and ITS was observed with sediment addition, which can be explained in the following ways:

- The organic matter absorbs a portion of the hydraulic binder hydration water, which leads to a decrease in hydration products such as C-S-H, ettringite and portlandite.
- Because of their physical characteristics (low dry density and high fine fraction), the sediments tend to decrease the compactness of the mix and consequently its strength.
- The presence of contaminants in the sediments interacts with the binders (lime and cement), which leads to a delay or inhibition of hydration reactions.

The addition of a granular corrector such as RCAs has the potential to improve mechanical strengths. Maherzi et al. [13] highlighted the beneficial effects of the granular addition in the mix composed of sediment, which leads to a reduction in the porosity of the materials and reduces the effect of impurity elements such as organic matter and sulfates.

3.4.2. Early Age Immersion Resistance

The early age immersion resistance of the mixes was evaluated using the ratio between UCSI and UCS60. Table 6 summarizes the results. This ratio must be higher than 0.6 for a material with an MBV ≥0.5 g/100 g.

Table 6. Water immersion effect on UCS.

Mixes	20S80G	30S70G	50S50G	100S
UCSI	1.80	1.41	1.38	0.8
UCS60	2.7	2.23	2.03	1.26
UCSI/UCS60	0.67	0.63	0.68	0.63

The results show that immersion decreased the compression strength of all mixes. However, it can be seen that all mixes have a UCSI to UCS60 ratio greater than 0.6. Therefore, all mixes meet the criteria for use in subgrade. These results are in the same range of those obtained in previous studies [9,10,13].

3.4.3. Long-Term Mechanical Behavior

The long-term mechanical properties (i.e., elastic modulus E and tensile strength TS) of the mixes were determined to evaluate whether they can be used in road subgrade construction. The tensile strength was determined using ITS. The mechanical properties were measured after 90 days of curing. For a use in subgrade, the couple of elastic modulus and strength must be at most of a resistance class 5 (zone 5). Figure 7 shows the classification of each mix. The results show that mixes 20S80G, 30S70G and 50S50G had a resistance class 3 while mix 100S had a resistance class 4. It can be concluded that mixes show adequate long-term mechanical performance for use in subgrade.

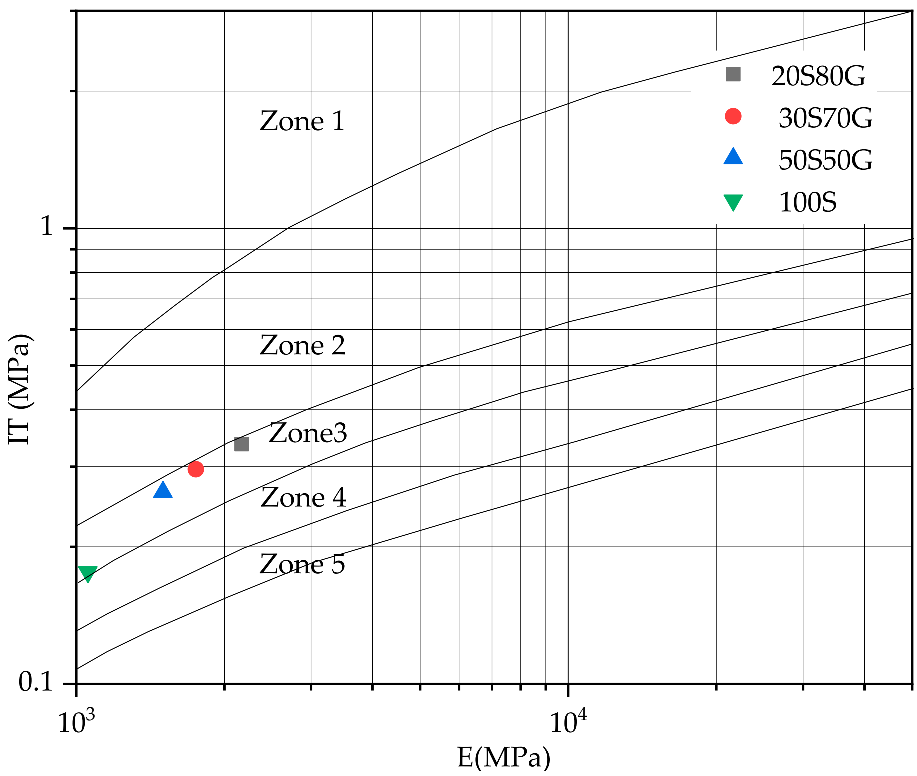

Figure 7. Mix mechanical strength development.

3.5. Environmental Assessment of Designed Materials

It is necessary to verify that the mix treatments did not have an impact on the environmental performance of the mixes, such as release of contaminants. Leaching tests were performed herein on the various mixes after 90 days of curing. Table 7 shows that all mixes comply with the thresholds of the SETRA guide, except mix 100S due to fluoride and sulfate amounts exceeding the thresholds. However, the values of the soluble fraction remain below the threshold. Thus, the mixes can be used in subgrade construction from an environmental point of view.

Table 7. Results of leaching test of mix.

	Units	**20S80G**	**30S70G**	**50S50G**	**100S**	**SETRA Guidelines for Alternative Materials (2011)**
As	mg/kg	<0.1	<0.1	0.13	0.19	2
Ba	mg/kg	0.33	0.34	0.35	0.22	100
Cd	mg/kg	<0.009	<0.009	<0.009	<0.009	1
Cr	mg/kg	0.29	0.27	0.21	0.24	10
Cu	mg/kg	1,0	0.90	0.87	0.82	50
Mo	mg/kg	0.41	0.42	0.54	0.47	10
Ni	mg/kg	0.33	0.34	0.39	0.38	10
Pb	mg/kg	<0.03	<0.03	<0.03	<0.03	10
Sb	mg/kg	<0.06	<0.06	<0.06	<0.06	0.7
Se	mg/kg	<0.08	<0.08	<0.08	<0.08	0.5
Zn	mg/kg	<0.01	<0.01	<0.01	<0.01	50
Fluoride	mg/kg	70	77	115.5	154	150
Chloride	mg/kg	1238	1619	2687.5	3445	15,000
Sulfate	mg/kg	4067	5371	9265	26,340	20,000
Soluble fraction	mg/kg	6785	8018	14,085	36,347	60,000

4. Conclusions

The study investigated the feasibility of using dredged sediments and recycled concrete aggregates in road subgrade construction. Several mixes were prepared using dredged sediments and recycled concrete aggregates. They were treated first with 1% (by mass) quicklime and then with 7% (by mass) cement for efficient treatment. The physical, mechanical, and geotechnical properties were determined using French testing standards. A detailed and thorough analysis of the results has confirmed the feasibility of using recycled concrete aggregates and dredged sediments up to a certain percentage in road subgrade construction. The study's major findings can be summarized as follows.

- The lime treatment improved the IBR values for the mixes. However, only mix 20S80G (i.e., 20% SED and 80%) is recommended for use in subgrade construction because its IBR reached a value of 20%.
- The mixes showed significant swelling volume reduction after lime treatment. Moreover, the mix swelling volumes were below the threshold of 5% for use in subgrade construction.
- The UCS and ITS values of the mixes increased with curing time. The mixes 20S80G, 30S70G, and 50S50G reached the circulation age requirement after 7 days, while mix 100S reached it after 28 days. On the other hand, mixes 20S80G, 30S70G, 50S50G reached the criterion of 0.25 MPa for use in subgrades after 7, 28, and 60 days, respectively.
- The mixes met the early age immersion resistance criteria for use in subgrade construction. The mix ratios between UCSI and UCS60 were higher than 0.6, which is the criteria for use in subgrade for a soil with an MBV $\geq$ 0.5 g/100 g.
- The mixes showed adequate long-term mechanical performance for use in subgrade construction, which corresponds to a resistance class of 5 or lower. Mixes 20S80G, 30S70G and 50S50G had a resistance class 3, while mix 100S had a resistance class 4.
- The mixes complied with the leaching thresholds of the SETRA guide, except mix 100S due to fluoride and sulfate amounts exceeding the thresholds. Thus, the mixes can be used in subgrade construction from an environmental point of view.

Finally, the mix containing the lowest amount of sediment (i.e., 20% of sediments and 80% of recycled aggregates) met all the characteristics suitable for a use in subgrade construction, i.e., an immediate bearing capacity greater than 20, unconfined compression strength greater than 1 MPa, indirect tensile strength greater than 0.25 MPa, UCSI/UCS60 ratio greater than 0.6, and a strength class of at most 5.

This study contributed a practical solution to address the disposal of the large quantities of dredged sediments and recycled concrete materials that are generated every year all over the world. Moreover, it contributed a solution to the depletion of high-quality raw materials for construction, which cannot be sustained. Dredged sediments and recycled concrete materials represent a viable alternative construction material. Future work will be focused on the feasibility of using dredged sediments and recycled concrete aggregates in foundations and base layers.

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