Journal of
Composites Science

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Use of Sewage Sludge for the Substitution of Fine Aggregates for Concrete

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Abstract: This work analyzes the use of sewage sludge, generated in wastewater treatment plants, as an alternative for small aggregate to be used in concrete. Concrete cylindrical specimens with height h = 20 cm and diameter D = 10 cm were prepared using different amounts of sludge in the substitution of fine aggregates. Portland cement (CP II Z 32 RS cement) was used in all concrete mixtures, and two water-cement ratios and four cement-sludge mixtures were investigated. Compressive strength, sclerometer index, ultrasonic wave transmission velocity, and water absorption capillary tests were performed. The results showed that the use of sewage sludge as a replacement for fine aggregate to produce concrete exhibited a positive effect on both its compressive strength and its capillary water absorption. The results, even preliminary ones, demonstrated that the sludge could be used as an effective replacement for fine aggregate to produce concrete. The replacement of fine aggregate with 5% sewage sludge proved to be the optimal replacement value for the type of sewage sludge investigated.

Keywords: sewage sludge; concrete; fine aggregate replacement; civil construction industry

Citation: Feitosa, M.C.A.; Ferreira, S.R.M.; Delgado, J.M.P.Q.; Silva, F.A.N.; Oliveira, J.T.R.; Oliveira, P.E.S.; Azevedo, A.C. Use of Sewage Sludge for the Substitution of Fine Aggregates for Concrete. *J. Compos. Sci.* **2023**, *7*, 21. https://doi.org/10.3390/jcs7010021

Academic Editor: Francesco Tornabene

Received: 16 December 2022
Revised: 2 January 2023
Accepted: 5 January 2023
Published: 10 January 2023

1. Introduction

The accelerating growth of the world population, accompanied by increasing urbanization and economic and industrial development, has increasingly demanded the construction and availability of sewage treatment, and, in this way, large amounts of sewage sludge are produced [1]. Sewage sludge from sewage treatment plants (STPs) is highly heterogeneous in composition and normally contains many organic and inorganic substances, in addition to high water content (higher than 95%) and high concentrations of heavy metals [2–4].

However, sewage sludge has a mineralogical composition similar to clay and Portland cement, as it contains important oxides such as SiO_2, Al_2O_3, CaO, and Fe_2O_3. Based on its chemical composition, sewage sludge is widely used in the production of building materials such as eco-cement, bricks, ceramic material, and lightweight aggregates (LWAs) or supplementary cementitious materials (SCMs) [5,6]. These applications, although in a very small way, offer alternative methods for sludge recycling and long-term resource savings.

Cement is the most used building material worldwide, and the cement industry is one of the main contributors to the high consumption of energy and natural resources as well as CO_2 emissions [7,8]. Thus, as a way of mitigating the environmental impact, several types of research have been developed to create eco-cements as alternative supplementary cementitious materials. These types of materials are often manufactured with materials from urban solid waste, waste from construction and demolition, and industrial by-products [9–11]. Indeed, in Japan, approximately 20% of the dry sewage sludge is used in the production of Portland cement [12].

The research of economically and environmentally advantageous solutions for the many types of solid wastes generated by human beings is still a challenge, and the final and adequate discharge of sewage sludge is one of the most important. The reuse of waste has proven to be a technically promising possibility as a raw material in the manufacture of products, namely in the building industry.

According to several authors [13–18], different ways of recycling sewage sludge as a building material have been suggested as safe alternatives to encapsulate heavy metals, reduce air pollutant emissions, and reduce the volumes needed to store that material in landfills. All these alternatives, appropriate to sustainable development, imply a consequent cost reduction, consisting of the beneficial use of the available raw material and energy, causing a reduction in the environmental resources' extraction, even in small quantities. Several studies with different applications using sewage sludge in civil construction have been developed in recent years, such as (a) light aggregates for concrete, thermal insulation, empty fillers, masonry, and floor blocks [16–19]; (b) raw material in the manufacture of ceramics [13,20]; (c) raw material in the manufacture of Portland cement and pozzolans [13,21]; and (d) supplementary material to produce mortars and concretes with Portland cement [22–24].

In 2018, the world's first book on recycled aggregate concrete structures [25], by J. Xiao, analyzed and discussed, in detail, the material properties and structural behavior of recycled aggregate concrete (RAC). In this work, the author shows that the ratio of building waste recycling in Tokyo had reached 58% in 1995, and the ratio for waste concrete was 65%, and the ratio for sludge was 14%.

In this context, this work studied the potential of using sewage sludge as a partial replacement for fine aggregate in the manufacture of structural concrete.

2. Materials and Methods

In the research experiments, sewage sludge from the Curado Sewage Treatment Plant (Curado STP), located in the metropolitan region of Recife, Pernambuco, was used. A physical, chemical, and microstructural characterization of the sewage sludge was presented in detail by Feitosa et al. [26]. The granulometric composition of the sewage sludge investigated consisted of 96% granulates (with dimensions between 4.8 mm and 0.05 mm) and 4% with dimensions smaller than 0.05 mm. The dry unit weight was 16.27 kN/m^3 with a percentage of sand and silt of 96% and 4%, respectively. Table 1 presents the chemical characterization of the sewage sludge used.

Table 1. Chemical characterization of the sewage sludge.

Properties	Sludge
pH in water	7.22
pH in KCl	7.30
Organic Carbon (g/kg)	14.29
Organic matter (g/kg))	24.64
Mg^{2+} exchangeable (cmol/kg)	11.00
Na^{+} exchangeable (cmol/kg)	185.80
K^{+} exchangeable (cmol/kg)	18.40
H^{+} + Al^{3+} extracted (cmol/kg)	8.90
H^{+} exchangeable (cmol/kg)	8.80
Value of V (% Sat. of Base)	0.97
% Fe_2O_3 in Ext. Sulfuric (g/kg)	2.25
% Al_2O_3 in Ext. Sulfuric (g/kg)	3.30
Electrical conductivity (mS/cm at 25 °C)	9769

2.1. Substitution of Fine Aggregates for Concrete

The experimental procedure was performed in three stages: (1) characterization of the raw materials (sand, gravel, cement, and sewage sludge); (2) studies of different mixtures in order to select four to produce concrete, three of them with different amounts of sludge regarding the dry weight of the sand and a standard mixture (reference-concrete) without sludge; and (3) evaluation of the mixtures in the fresh and hardened states.

Initially, two concrete mix ratios were prepared: (a) one referred to as 1:0.54:1.54-cement, fine and coarse aggregates, all measured in mass, with a water-cement ratio (w/c) equal to 0.57, and another (b) referred to as 1:2.5:2.34-cement, fine and coarse aggregates, all measured in mass, with w/c = 0.65.

This was done to compare the results of the present study with other previous studies that investigated the use of sewage sludge as a construction material. Furthermore, the evaluation of the compressive strength of concretes with aggregates from construction and demolition waste (CDW) [27] was analyzed, and the potential of the sewage sludge ash (SSA) as supplementary material for the production of concretes with Portland cement [22–24] was studied. Finally, four cement-sludge mixtures were prepared with 5%, 10%, and 15% of the dry-weight sludge, in partial replacement of the sand. These replacement values were used to allow comparison of the results with previous research [27], which used the same percentages of sludge in substitution for fine aggregates.

In summary, the materials used in the manufacture of concrete were:

- Portland cement resistant to sulfates CP II Z 32 RS, produced according to Brazilian standards;
- The aggregates used in the manufacture of concrete were washed quartz sand and crushed stone measuring 25 mm. The main physical parameters of the fine and coarse aggregates were analyzed according to NBR NM 19 recommendations [28];
- The water used for the production of concrete came from the supply concessionaire of the city of Recife.

A concrete mixer with a capacity of 110 L was used to produce the concrete. The design strength of the concrete at 28 days was 25 MPa. The concrete manufacturing process followed these steps: (a) First, the coarse aggregates were added, followed by the fine aggregates and half of the predicted water; (b) the concrete mixer was then activated for 1 min, in order to promote mixing between the sand and the gravel; (c) the cement and the remaining water was added.

Four concrete mixtures were prepared. One to be used as the reference (without the addition of sewage sludge), and the other three with sludge in dry weight proportions of 5%, 10%, and 15% in partial replacement of the fine aggregates. The details of the concrete mixtures produced as well as the consumption of the materials used are shown in Table 2. In order to make the comparison possible, the same reference mixture was chosen from the research performed with concrete using construction and demolition waste [27] and sewage sludge ash [22]. The sludge was used under the conditions in which it was collected in the field, with only air-drying and sieving operations on a 4-mm mesh of all collected samples. The final hygroscopic water content of the sludge obtained was 2.48%. In all concrete mix compositions made with sludge, the w/c was adjusted to take into account the water content.

Concrete molding was performed according to Brazilian standards [29–33]. For each concrete manufactured, nine cylindrical specimens of 0.10 m in diameter and 0.20 m in height were molded. The concrete slump test, or slump cone test, was used to determine the workability or consistency of the concrete mix prepared [30]. The slump was kept constant (90 $\pm$ 10 mm). Figure 1 exhibits a view of the concrete slump test performed. Subsequently, after a period of 24 h, the specimens were demolded and immersed in a tank with water until completing the planned ages for the tests–7, 14, and 28 days.

Table 2. Concrete mixtures and material consumption per m^3 (w/c = 0.57 and w/c = 0.65).

Main Mixture Features		Unitary Concrete Mixture	Cement (kg)	Fine Aggregate (kg)	Sludge (kg)	Course Aggregate (kg)	Water (kg)
w/c = 0.57	Fine aggregate (sand)	1: 1.50: 2.50	423.10	634.65	-	1057.75	241.17
	Sand + 5% Sludge	1: 1.51: 0.08: 2.59	371.28	560.63	29.70	961.62	211.63
	Sand + 10% Sludge	1: 1.32: 0.15: 2.47	388.75	513.5	58.31	960.21	221.59
	Sand + 15% Sludge	1: 0.80: 0.14 1.57	395.69	316.55	55.40	621.23	225.54
w/c = 0.65	Fine aggregate (sand)	1: 2.33: 2.85	342.85	798.84	-	977.12	222.85
	Sand + 5% Sludge	1: 2.21: 0.12: 2.18	343.88	759.97	41.26	749.66	223.52
	Sand + 10% Sludge	1: 1.44: 0.16: 2.53	384.91	554.27	61.58	973.82	250.19
	Sand + 15% Sludge	1: 1.08: 0.19: 2.14	419.63	453.20	79.73	898.01	272.76

Figure 1. Slump cone test method.

2.2. Methods

Forty-eight standard concrete cylinder specimens were prepared to perform the planned tests—compressive strength, sclerometer tests, and ultrasonic pulse velocity tests. Twenty-four other standard concrete cylinder specimens were prepared to perform the capillary water absorption tests. For each test performed, two specimens for each cement-sludge mixture were prepared, except for the capillary water absorption test, where three specimens were used. The experimental campaign was performed in the Materials Laboratory of the Catholic University of Pernambuco in accordance with the following NBR standards: NBR 7222 [29], NBR 7584 [31], NBR 8802 [32], and NBR 9779 [33].

2.2.1. Compressive Strength Test

All necessary care was taken to ensure that the upper and lower cross sections of all specimens were completely uniform and flat.

After grinding the specimens, the tests were performed using a digital universal testing machine—MUE—with a capacity of 1000 kN. The specimen was placed directly on the press so that it was centered with respect to the loading axis. The specimens were tested in compression at the ages of 7, 14, and 28 days (see Figure 2).

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

Figure 2. Compressive strength test view: (**a**) sample in the press, (**b**) broken sample, and (**c**) rupture of the specimen (age of 28 days and 15% sludge).

2.2.2. Sclerometric Test

The sclerometric test is a kind of check, very rapid and agile, enabling, without damaging the investigated areas, to examine a considerable number of structures in a short time. It also enables the evaluation of the possible concrete compressive strength by establishing the related impact hardness provided by the used tool. The test is performed by placing the sclerometer in contact with the surface after treatment with a medium-grain abrasive stone in carborundum, in the perpendicular direction, and measuring the rebounds of a steel cursor pushed hard on the surface. Nine readings were performed for each specimen, and their results, arithmetically averaged, were used to obtain the sclerometric rebound index. With this value, it was possible to extrapolate from correlation diagrams to obtain the estimated cubic concrete compressive strength of the specimen tested together with its related dispersion.

2.2.3. Ultrasonic Pulse Velocity Test

Ultrasonic measurements are often used in engineering to determine concrete properties, such as strength and elastic modulus, and allow some qualitative information regarding the quality and deterioration of the material. Velocity, attenuation, frequency, and energy are examples of ultrasonic wave propagation properties that can be used to obtain that information.

In the research, ultrasonic pulse velocity (UPV) testing was used to determine the integrity and quality of structural concrete by measuring the speed and attenuation of an ultrasonic wave passing through the concrete specimens. To do that, direct transmission was used associated with a Pundit ultrasonic pulse velocity tester using longitudinal 54 kHz transducers.

The method consists of measuring the displacement time of an ultrasonic pulse that passes through the concrete being tested using a simple calculation to compute the propagation speed of the waves. With this information, it is possible to infer about the concrete quality, taking into account that the higher the speed, the better the quality of the examined concrete. Figure 3 illustrates the procedure for this test.

Figure 3. Ultrasonic Velocity Test.

2.2.4. Capillary Absorption Test

After 28 days of curing the concrete, the specimens were weighed, placed in an oven at a temperature of 105 ± 5 °C for 24 h, and weighed again until they reached a constant mass, according to the standard criteria. Then, the samples were placed in a closed container with a constant water depth of 5 ± 1 mm, determining the mass of the specimens after 3, 6, 24, 48, and 72 h of contact with water. In sequence, the samples were submitted to the split tensile test in order to allow for the verification of the water distribution inside them. Figure 4 exhibits some steps of the test performed.

(**a**) (**b**) (**c**) (**d**)

Figure 4. Capillary absorption test: (**a**) specimen immersed in water; (**b**) hand press; (**c**) broken specimen; (**d**) absorption by the specimen.

The water absorption by capillarity was calculated with the following equation:

$$A = (m - m_d)/S \quad (1)$$

where A is the water absorption by capillarity (g/cm^2), m is the mass of the specimen that remains with one side in contact with the water for a specified period of time (g), m_d is the mass of the dry specimen as soon as it reaches the temperature of (23 ± 2) °C (g), and S is the cross-sectional area (cm^2).

3. Results and Discussion

Figure 5 exhibits the granulometric curves for the fine and coarse aggregates as well as for the sludge that was partially used as fine aggregate replacement. The results showed that the fine aggregate presented a fineness module of 2.57 and a density of 2.65 g/cm^3, and the coarse aggregate exhibited a fineness module of 7.38.

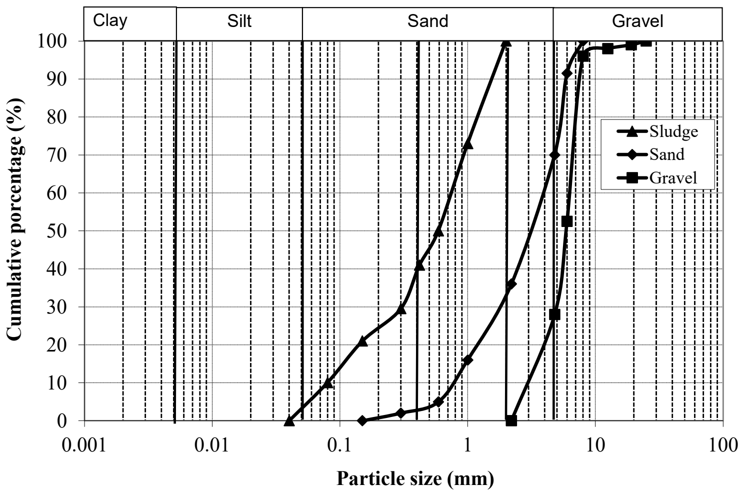

Figure 5. Particle size distribution of the aggregates.

The ultrasonic velocity values for the concrete mixtures with a w/c ratio equal to 0.57 and w/c = 0.65, in the function of different healing times obtained in the tests, are shown in Figure 6, as well as the results presented by [27] for concrete made with construction demolition waste (CDW).

The results showed that the values of ultrasonic velocity decreased with the percentage increase of the sludge content; however, these values were higher than the values obtained by [27] for concrete made with CDW. However, the UPV values for the two concrete samples (see Figure 6) analyzed were within the range that characterizes the concrete as good quality; i.e., UPV values between 3500 m/s and 4500 m/s [34].

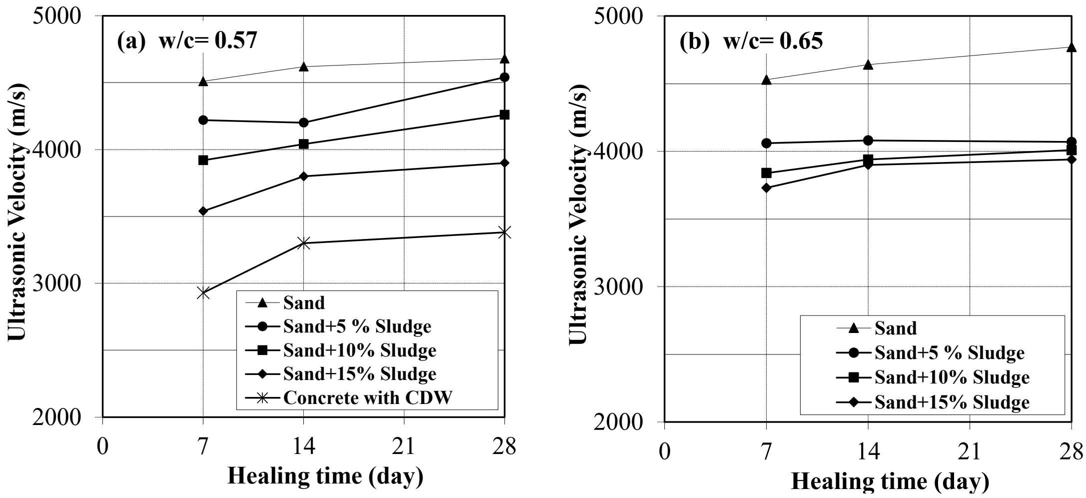

Figure 6. Ultrasonic velocity versus healing time for: (**a**) conventional concrete, concrete with sewage sludge, and with CDW [27] for w/c = 0.57; and for (**b**) conventional concrete and concrete with sewage sludge for w/c = 0.65.

Figure 7 showed the average values of the sclerometer index values in function of the healing time, obtained in the tests, and the results presented by [27] for comparison purposes. The results obtained showed that sclerometer index values decreased with the increase in sludge content for both w/c ratios investigated −0.57 and 0.65. A comparison with concrete made with CDW, presented by [27], showed lower sclerometer index values than the values obtained by [27]. The justification for this behavior may be associated with the different characteristics of construction and demolition waste compared to sewage sludge. Figure 7 also showed that the increase in sludge percentage, as an aggregate, decreased the sclerometer index for the same healing time. However, the water/cement ratio was not sensitive to the concrete-sludge mixture.

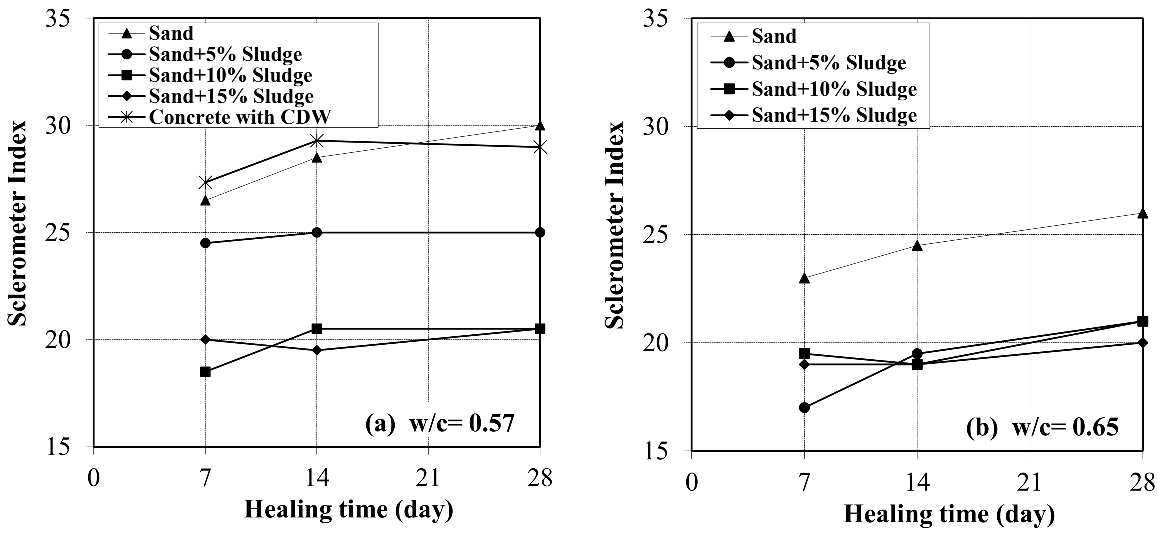

Figure 7. Sclerometer index versus healing time: (**a**) conventional concrete, with sewage sludge and with CDW [27], w/c = 0.57 and (**b**) conventional concrete with sewage sludge, w/c = 0.65.

The values of compressive strength versus healing time are shown in Figure 8, with the results of concrete made with CDW presented by [27]. Some concrete design codes impose a minimum value of 20 MPa for concrete to be considered structural concrete. In the research, the concrete made with 5% sludge as a replacement for the fine aggregate exhibited that value for a w/c ratio of 0.57 and a healing time of 14 days. For the other w/c studied (0.65) and for the other amount of sludge used, the reference values of concrete strength were not obtained, and none of the healing times were investigated. The same behavior was observed in previous research [35,36].

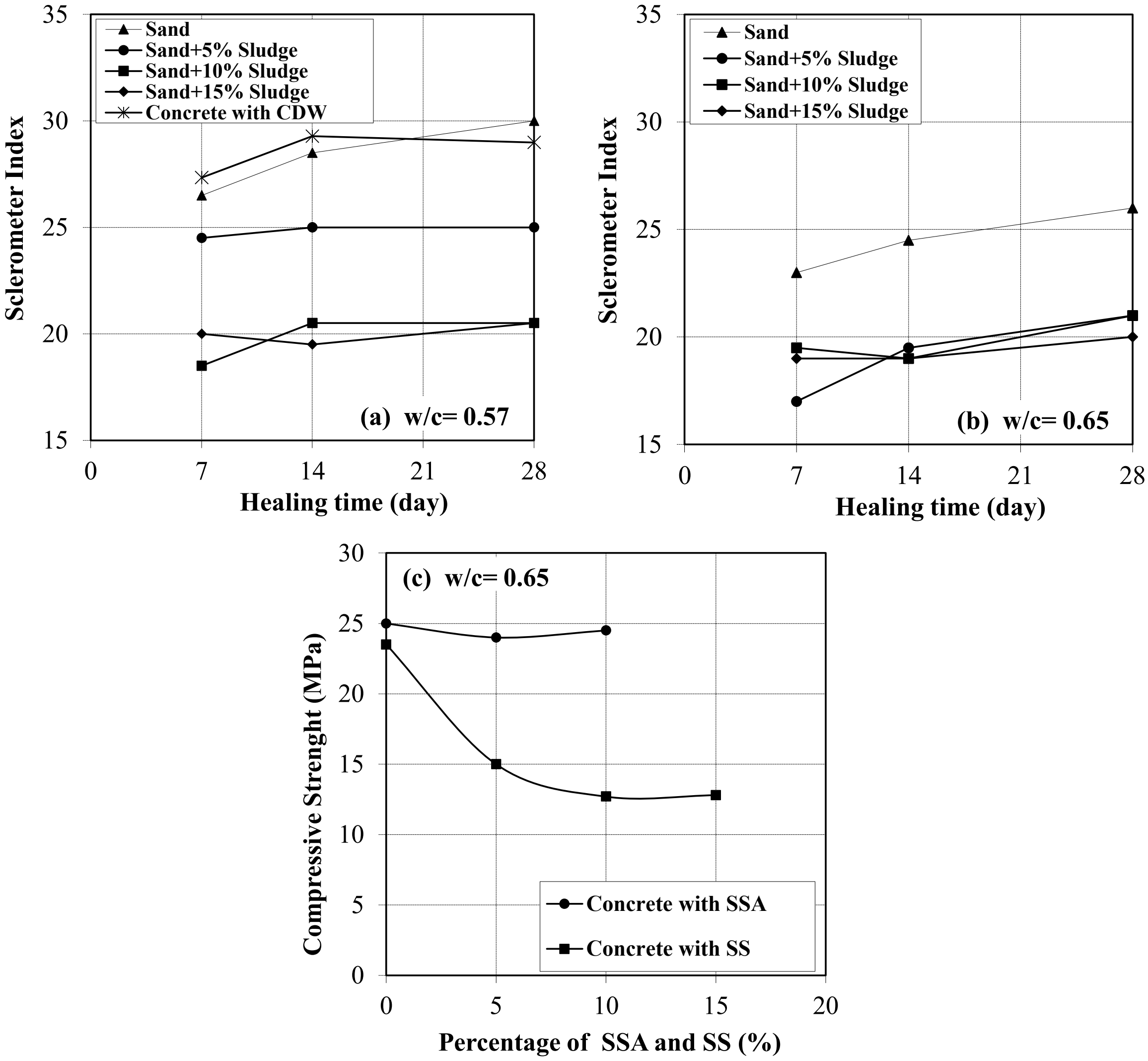

Figure 8. Compressive strength versus healing time: (**a**) conventional concrete, with sewage sludge and with CDW [27], w/c = 0.57; (**b**) conventional concrete with sewage sludge, w/c = 0.65.; and (**c**) concrete with sewage sludge (SS) and sewage sludge ash (SSA) [23], w/c = 0.65.

In summary, the increase in the amount of sludge added to the concrete as fine aggregate replacement contributed to the decrease in its compressive strength and exhibited values close to those obtained in concretes made with CDW aggregate (Figure 8a). It can be observed that the compressive strength decreased with the increase in sludge percentage up to 10%, and for further additions, it presented a value close to that obtained with concrete made with CDW [27], for a w/c of 0.57. For concrete with w/c = 0.65, a decrease in the material strength was observed when the sludge content was increased, and a significant reduction was achieved with the addition of sewage sludge ash (SSA) [23].

The results of water absorption values by capillarity after 72 h are presented in Table 3, and the results of capillarity water absorption versus time are illustrated in Figure 9. It is possible to observe a decrease in the values of capillary water absorption pressure (see Figure 9) obtained with the increase in the amount of sludge added—63% for the ratio w/c = 0.57 and 52% for w/c = 0.65. In addition, the capillary pressure values obtained for concrete in proportions of 5%, 10%, and 15% of sludge are of the same order of magnitude.

The increase in the percentage of sludge added to the concrete as aggregate decreases capillary water absorption, regardless of the percentage of sludge added.

Table 3. Capillary absorption test result after 72 h.

Samples	Capillary Water Absorption (%)	
	w/c = 0.57	w/c = 0.65
Sand	2.78	2.09
Sand + 5% sludge	2.12	1.33
Sand + 10% sludge	1.87	1.57
Sand + 15% sludge	2.41	1.49

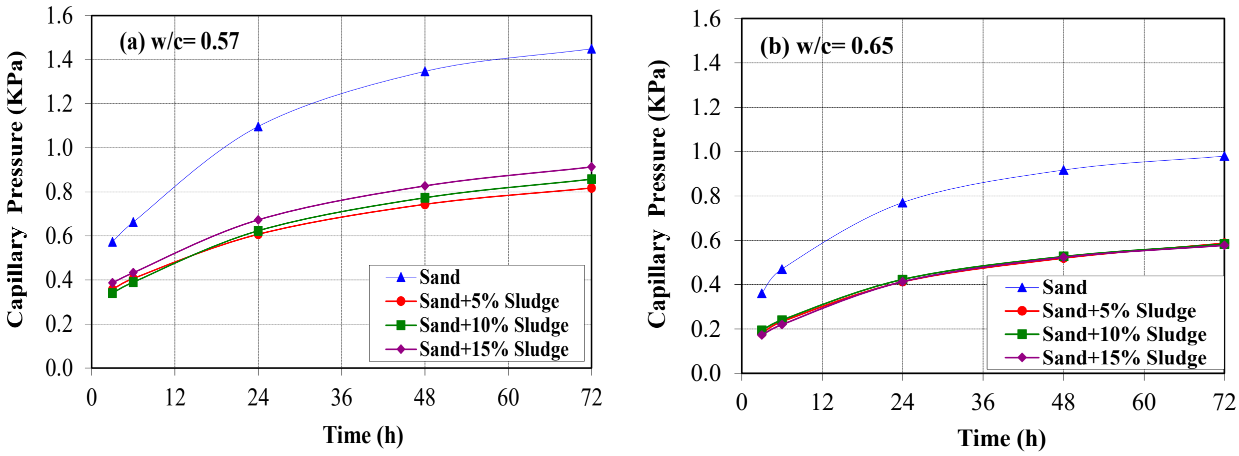

Figure 9. Capillary water absorption pressure versus time, with conventional concrete and concrete with sewage sludge: (**a**) for the ratio w/c = 0.57; and (**b**) for the ratio w/c = 0.65.

The interaction between water and air existing in the concrete pores generates capillary pressure, and the amount of water that will be absorbed by the pore is a function of the capillary suction pressure. Thus, the addition of dehydrated sludge as fine aggregate to concrete generates larger pores for the same volume of voids, reducing capillary pressure. According to Neville [37], absorption is not considered a measure of concrete quality; however, it is observed that good-quality concrete presents absorption below 10%. In this case, the absorption was below 3%, which can be classified as good-quality concrete.

The low level of absorption obtained–close to 3%–indicates that the concretes made with the sludge amounts investigated, used as a replacement for fine aggregates, can be concrete of good quality. In fact, all the absorption levels of the concrete made with sludge in substitution for sand in the concrete mixture were less than the absorption values for concrete made with usual fine aggregates.

4. Conclusions

Sewage sludge cannot be considered a single waste, as each sewage treatment plant presents different sludge, and consequently, each STP must be treated as unique in a reuse or recycling process. This work with sewage sludge obtained from Curado STP contains data and information relevant to new research on this topic in order to complement and/or confirm the results obtained.

The experimental results showed that concretes with more than 5% sewage sludge addition restrict their application, mainly because they have a compressive strength of less than 15 MPa.

In summary, this work shows that the use of sludge as a fine aggregate partial substitution in concrete could be a viable, environmentally friendly, and more adequate alternative, namely, to produce concretes with compressive strengths not much higher than 20 MPa. The use of sewage sludge promotes the reduction of considerable quantities of this material to be discharged in landfills or returned to watercourses, as well as significant reductions in the consumption of natural aggregates.

Author Contributions: All the authors contributed to the development, analysis, writing, and revision of the paper: conceptualization, M.C.A.F., F.A.N.S., S.R.M.F. and J.M.P.Q.D.; methodology, J.M.P.Q.D. and F.A.N.S.; formal analysis, M.C.A.F., S.R.M.F., J.T.R.O. and P.E.S.O.; investigation, M.C.A.F., S.R.M.F., J.T.R.O. and P.E.S.O.; writing—original draft preparation, M.C.A.F., S.R.M.F., F.A.N.S., A.C.A. and J.M.P.Q.D.; writing—review and editing, M.C.A.F., S.R.M.F., F.A.N.S., A.C.A. and J.M.P.Q.D.; visualization F.A.N.S., A.C.A. and J.M.P.Q.D.; supervision, F.A.N.S., A.C.A. and J.M.P.Q.D. All authors have read and agreed to the published version of the manuscript.

Funding: This work was financially supported by: Base Funding-UIDB/04708/2020 and Programmatic Funding-UIDP/04708/2020 of the CONSTRUCT-Instituto de I&D em Estruturas e Construções-funded by national funds through the FCT/MCTES (PIDDAC); and by FCT–Fundação para a Ciência e a Tecnologia through the individual Scientific Employment Stimulus 2020.00828.CEECIND.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available upon request from the authors.

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

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