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Sewage Sludge Valorization for Collapsible Soil Improvement

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Abstract: The environmental problems caused by sewage sludge generated by the growth of the global population and urbanization are drawing the attention of the scientific community worldwide to the need of developing sustainable solutions to use that material. This work investigated the possibilities of using sewage sludge, generated in wastewater treatment plants, as a strategy to improve and stabilize collapsible soils. Different soil–sludge mixtures, with 5%, 10%, and 15% of sludge, were analyzed. For the characterization and analysis of the soil–sludge interaction, physical, chemical, and edometric experiments were performed. The results showed that the addition of sludge to the soil causes a void index reduction, improves particle packaging, and reduces soil collapsibility to the same specific dry apparent weights, i.e., showed to be a promising method for the improvement of collapsible soils.

Keywords: sewage sludge; soil–sludge interaction; soil improvement; collapsible soil; civil construction industry

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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. Sewage Sludge Valorization for Collapsible Soil Improvement. *Buildings* **2023**, *13*, 338. https://doi.org/10.3390/buildings13020338

Academic Editor: Cinzia Buratti

Received: 7 January 2023
Revised: 16 January 2023
Accepted: 17 January 2023
Published: 24 January 2023

1. Introduction

One of the main environmental problems to be solved nowadays is the large amount of waste of several origins that is generated in urban centers worldwide. Solid waste management is one of the greatest costs to municipal budgets in developing and under-developing countries and its inadequate disposal can be a contaminating agent of natural resources that significantly affects the quality of life of the population. To deal with this issue, environmental protection laws have been created to establish safe sewage sludge and waste management strategies. In large cities, environmental legislation increasingly restricts the waste discharges in landfills, as well as decreases the number of landfills, and enlarges the costs associated. In this context, it is necessary to develop and implement alternatives that efficiently decrease the waste discharges in landfills [1,2].

In Brazil, the Environment Ministry estimates that about 10% of urban sewage is treated at sewage treatment plants (STPs) before being released into streams. This treatment results in the production of a sludge rich in organic matter and nutrients called sewage sludge, whose final disposal is problematic, representing 60% of the operation cost of treatment plants [3]. The inadequate final discharges of this material partially nullify the benefits of effluent collection and treatment. Therefore, an adequate destination must be given to these residues and, in the last decades, several studies have been performed to investigate the possibilities to recycle this waste for using as raw material for the production of other materials [4,5].

Previous investigations [6–9] discussed the possibility to use sewage sludge as a soil fertilizer due the high amount of organic matter but the total concentration of heavy metals such as Cu, Zn, Hg, Pb identified by the authors demanded additional tests to avoid the absorption of these heavy metals by plants.

Incineration of sewage sludge has been already investigated [10,11] and the results showed that its mass reduction was more than 70% and its volume decrease was more than 90%. Despite this efficiency, the authors highlight that this is a temporary solution to reduce the volume of existing sewage sludge and the amount of sewage sludge from STPs keeps on increasing, due to the constant increase in the world population and urbanization, and more perennial solutions are still needed.

The environmental risks generated by sewage sludge are well-known but a still persistent increase in its production in the last decades demands further investigations regarding the most adequate way to deal with this issue.

Collapsible soils are defined as any unsaturated soil that goes through a radical rearrangement of particles and a great decrease in volume upon wetting, additional loading, or both. They can affect the building construction process and its uses and, in some situations, they can cause severe damage to canals, dams, pumping plants, power plants, pipelines, roads, and buildings [12]. Taking into account this fact, extensive studies have been performed to establish strategies to stabilize or mitigate their detrimental behavior [13–16]. The growth of urbanization and the expansion of large cities, combined with the limited availability of available land, has led to the construction of buildings on collapsible soils and this situation increasingly requires greater control of the stability and improvement strategies of these kinds of soils [17–21].

The use of sewage sludge ash (SAS) as a part to be incorporated into the materials used for soil stabilization has been developed [8–10,22]. Munjed and Mousa [23] showed that the addition of SAS increases the maximum dry density and the unconfined compressive strength of the stabilized soil. More, Deng et al. [24] showed that SAS is a good material for stabilizing soft and cohesive subgrade soil properties. Mosallaei et al. [12] analyzed the effect of SAS on the collapsible soil shear strength parameter and the results showed that the soil cohesion increases and the internal friction angle decreases with the percentage of sewage sludge ash used as an additive.

The importance of mitigating the impact of sewage sludge from STPs on the environment and reducing the possibilities of spreading its effects still demands scientific investigations focused on alternative ways to reuse that material. In this context, the paper presents the results of an investigation regarding the use of SAS as a strategy to improve the behavior of collapsible soils.

2. Materials and Methods

2.1. Materials

The soil investigated was collected at the Itapirema Experimental Station of the Agronomic Institute of Pernambuco (IPA) locate in the of Goiana, 65 km far from the Capital Pernambuco State. The soil is classified as spodosol and the samples were obtained from the 0–20 cm layer using a conventional auger. The material was air-dried and manually crushed, homogenized. After that, the soil was sieved through a mesh of 4.8 mm for particle size analysis by sieving and sedimentation methods, and it was determined by its consistency limits. The preparation of soil samples for the physical characterization tests was made in accordance with Brazilian standards [25–31].

The standard [25] deals with the determination of the swelling coefficient of aggregates, which is defined as the ratio between the wet and dry volumes of the same aggregate mass. Swelling of fine aggregate caused by the absorption of free water by the aggregate grains results in a change in apparent volume, which changes the unit mass [25]. The standard [26] specifies the procedures for the particle size analysis of soils, which can be performed by sieving or by a combination of sedimentation and sieving. It is the study of the size of the particles or grains that make up the soil. It determines the percentage of the soil in a given particle size range, which is used as a guide to the classification and behavior of the soil. The standard [27] deals with the determination of specific gravity, apparent specific gravity, and water absorption. Standard [28] specifies the procedures for determining the Atterberg limit, which is used to describe a physical state, i.e., the degree of bonding between soil particles. The standard [29] describes the method of determining the plasticity limit and calculating the plasticity index of soils, and the standard [30] describes a method of determining the relationship between the moisture content and the apparent specific dry mass of soils in the compacted state according to the specified procedures.

Figure 1 exhibits the sewage sludge collected from a sage treatment plant, located in the Metropolitan Region of Recife, Pernambuco, that was used in the experimental campaign. The collected sludge was packed in plastic bags to be transported and air-dried in a laboratory. It was then ground and sieved with a 4.8 mm mesh opening sieve in order to evaluate the potential of this material. Then, physical, chemical, mechanical, compressibility, and collapse tests were performed.

(a) (b)

Figure 1. (a) Dry sludge and (b) sieved sludge obtained from a STP.

The results presented in Table 1 show that the sludge used meets the heavy metal limits defined by the Resolution of the National Environment Council Conama 375/06 [31]. Finally, different soil–sludge mixtures, with 5%, 10%, and 15% of sludge were analyzed.

Table 1. Metal contents present in the sewage sludge investigated.

Maximum Concentration (mg/kg Dry Mass)		
Metal	**STP**	**CONMA 375/06**
As	0.41	41
Ba	242.45	1300
Cd	1.86	39
Pb	9.66	300
Cu	20.89	1500
Cr	10.49	1000
Hg	0.16	17
Mo	23.21	50
Ni	8.73	420
Se	0.22	100
Zn	86.54	2800

2.2. Methods

2.2.1. Physical Characterization

The physical characterization tests were performed according to NBR standards, namely: sample preparation (NBR 6467 [25]), particle size analysis (NBR 7181 [26]), soil grain specific mass (NBR 6458 [27]), liquid limit determination (NBR 6459 [28]), plasticity limit determination (NBR 7180 [29]), compaction test (NBR 7182 [30]), and in the conventional single and double edometric tests (NBR 16853 [32]). Figure 2 presents a view of the natural soil analyzed.

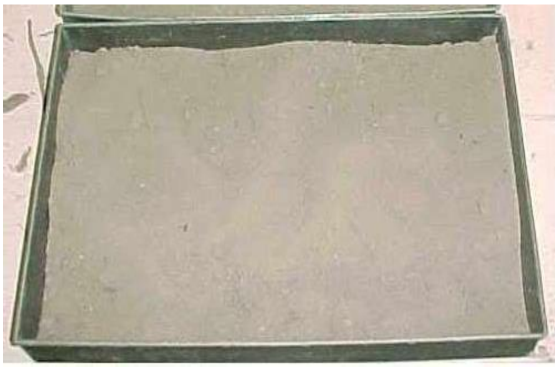

Figure 2. Natural soil–Silt sand.

2.2.2. Chemical Characterization

The chemical characterization tests of the soil, sludge, and soil–sludge mixture were performed according to the methodologies established by the National Service of Soil Survey and Conservation and using the Manual of Soil Analysis Methods of the Brazilian Research and Agriculture Companies [33]. The chemical tests included the determination of the following information:

- pH—the pH in the soil and sludge samples indicates the presence of exchangeable aluminum and also the predominance of clay in weathering process, which is verified by the variation of the pH in water and the pH in KCl;
- Organic carbon and organic matter—the amount of organic matter in the soil defines the formation of a greater or lesser amount of aggregate in the structure, and aggregates formed by organic matter contents higher than 3.5% are considered unstable;
- Exchangeable acidity—the actual acidity is used to determine the effective cation exchange capacity (CTC), also defined as the sum of bases;
- Electrical conductivity—the electrical conductivity in the saturation extract defines the amount of existing salts (cations and anions);
- Specific surface area and methylene blue adsorption—the larger the specific surface area of the clay mineral, the greater the amount of methylene blue adsorbed and the smaller the particle size.

2.2.3. Scanning Electron Microscopy

The microstructures of the soil and soil–sludge mixtures were observed from the samples carefully collected and air-dried. Three prismatic specimens with dimensions of 9.8 mm (width) and 8 mm (height) were prepared. The specimens were fixed in an aluminum cylinder with a diameter of 9.8 mm and a height of 11 mm, with 3M tape and glue on the contact surface. The samples were placed in the Fine Coat Ion Sputter JfC 1100 (JEOL, Tokyo, Japan) type vacuum bell for metallization to receive a thin film of gold to provide good electron beam conduction. After the metallization process, the surfaces of the samples were observed and photographed in the JSM LV1600 (JEOL, Tokyo, Japan) scanning microscope equipment operating at 15 kV.

2.2.4. Double and Single Oedometer Test

The soil samples were placed to dry in the open air. They were crushed and passed through a nº. 10 sieve. To determine the hygroscopic moisture, a sample of approximately 1 kg was separated from the natural soil and the sludge. After determining the hygroscopic moisture of the natural soil (1.60%) and the sludge (2.48%), water was added to the natural soil sample and to the three mixtures with 5%, 10%, and 15%. This was performed in order to achieve a value of 5.0% moisture content. The samples were placed in a plastic bag for moisture equalization (five days), and then the volume of soil required to achieve the desired dry apparent specific weights was calculated. After that, with the soil and soil–sludge samples at the desired moisture content, the volumes of soil required for compaction of the specimens were calculated with specific dry weights of 15.0 kN/m^3 and 17.0 kN/m^3 with degrees of compaction of 82% and 94%, respectively, at 5% of moisture content, in situ, corresponding to an optimal moisture content deviation of 3.66%.

To minimize moisture and soil losses due to mold manipulation, the samples were compacted in the edometer cell rings, which had an average height of approximately 20 mm and a diameter of 76.25 mm.

The compaction was statically performed in a compression press with a capacity of 50 kN. The soil volume, previously calculated, was placed in the ring and embedded in the compaction mold. The shape of the mold ensured that the soil was not compacted further than necessary, due to the safety system at the top, where there is a contact of the piston with the top of the mold, preventing the piston from further compacting the soil (see Figure 3).

(a) (b)

Figure 3. Compression mold at the beginning and after static compression: (**a**) Mold in the press at the start of compaction; (**b**) Mold after compaction.

The oedometer tests, single and double, were performed in a bishop's press with a 1:10 ratio arm and cells with a fixed ring. Strain readings were monitored using a strain gauge, with a sensitivity of 0.01 mm. The natural soil and soil–sludge mixture samples, in weight proportions of 5%, 10%, and 15%, were statically compacted with the moisture content at about 5% $\pm$ 0.12% with a coefficient of variation of 2.16, and a dry apparent specific weight of 15.00 $\pm$ 0.02 kN/m^3 with a coefficient of variation of 0.15%, and 17.0 $\pm$ 0.03 kN/m^3 with a coefficient of variation of 0.21%. The samples were confined laterally, and distilled water was used for flooding. Fifty-six samples were used in single oedometric tests and sixteen samples in double oedometric ones.

At the beginning of the tests, a minimum stress of 3.75 kPa was applied to the system to perform the initial strain readings. This was a necessary settlement resulting from this stress attributed to the accommodation of the system, and was not considered in the strain calculations.

The molding of the samples (moisture control, compaction mold, control of the weights, and static compaction technique) resulted in specimens with the reproducibility and repeatability of the expected conditions, presenting physical indexes with a small variation of values in relation to the desired ones. Vertical stresses were applied incrementally ($\Delta\sigma/\sigma$ = 1) starting with 10 kPa and reaching 640 kPa. The duration of each stress stage was such that the stress between the two consecutive time intervals ($\Delta t/t$ = 1) was less than 5% of the total soil deformation that occurred up to the previous time. The flood of the specimens was performed with distilled water and 56 specimens were prepared.

3. Results

3.1. Physical Characterization of Soil, Sludge and Soil-Sludge Mixtures

According to the U.S. Soil Taxonomy classification, the soil used is a *spodosol*. Its composition is 88% sand, 3% silt, and 9% of clay (Table 2). It is a silty sand (SM) in the Unified Soil Classification (USC), non-liquid and non-plastic, and in the TRB classification system is classified as boulders and silts or clayey sands (A-2-4).

Table 2. Dry unit weight (γ_d), percentage of sand, silt, and clay in the materials analyzed and physical indexes (ideal moisture. w_{opt}, and maximum apparent dry specific weight, γ_{dmax}).

Material	γ_d (kN/m^3)	Sand (%)	Silt (%)	Clay (%)	Classification		w_{opt} (%)	γ_{dmax} (kN/m^3)
					Unified	TRB		
Soil	26.16	88	3	9	SM	A-2-4	8.66	18.18
Sludge	16.27	96	4	0	–	–	–	–
Soil + 5% sludge	23.99	90	3	7	SM	A-2-4	12.34	17.66
Soil + 10% sludge	23.54	92	4	4	SM	A-3	13.28	18.14
Soil + 15% sludge	22.84	92	4	4	SM-SP	A-2-4	12.46	15.85

The granulometric composition of the sewage sludge investigated consisted of 96% of granulates (with dimensions between 4.8 mm to 0.05 mm) and 4% with dimensions smaller than 0.05 mm, as presented in Figure 4.

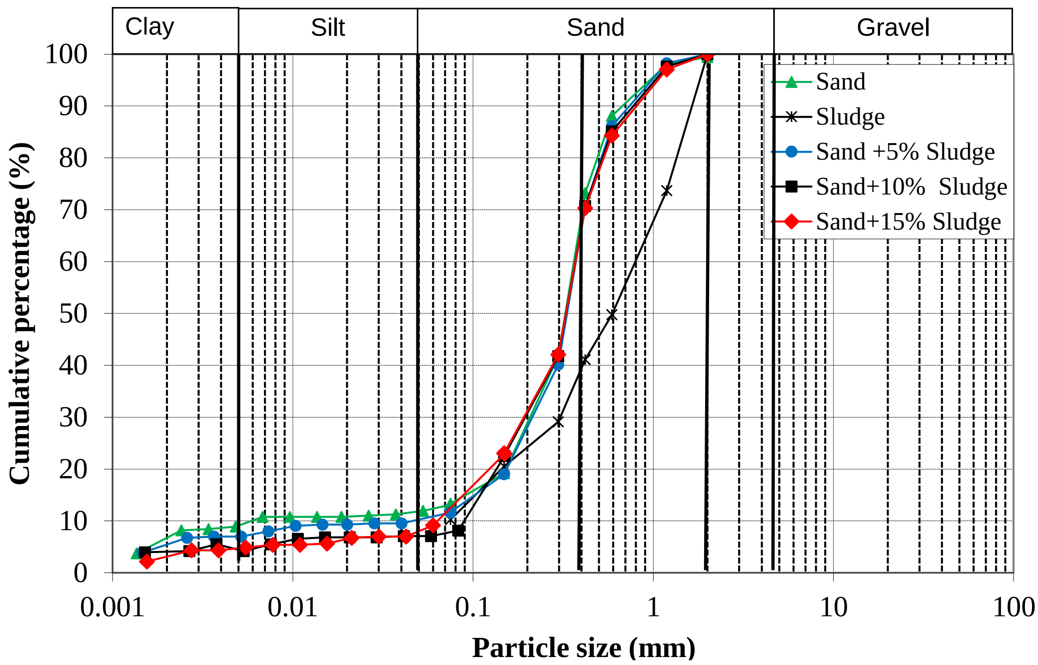

Figure 4. Particle soil distribution, sewage sludge, and different soil–sludge mixtures analyzed.

Soil mixtures with sewage sludge in proportions of 5% and 10% are classified, also as silty sand (SM), non-liquid, and non-plastic. The soil–sludge mixture with 15% of sludge is classified as poorly graded silty sand (SM-SP), non-liquid, and non-plastic. In the TRB classification system, the mixtures with percentages of sludge of 5% and 15% are classified as boulders and silts or clays sands (A-2-4), and the mixture with 10% is a fine sand (A-3).

Figure 5 shows that the addition of sludge to the soil increases the ideal moisture (w_{opt}) up to an amount of 10% of sludge and exhibits a small decrease up to 15% of sludge. The maximum dry apparent weight does not change until the increase of 10% of sludge, but it experiences a decrease for values of 15% of sludge added to the soil.

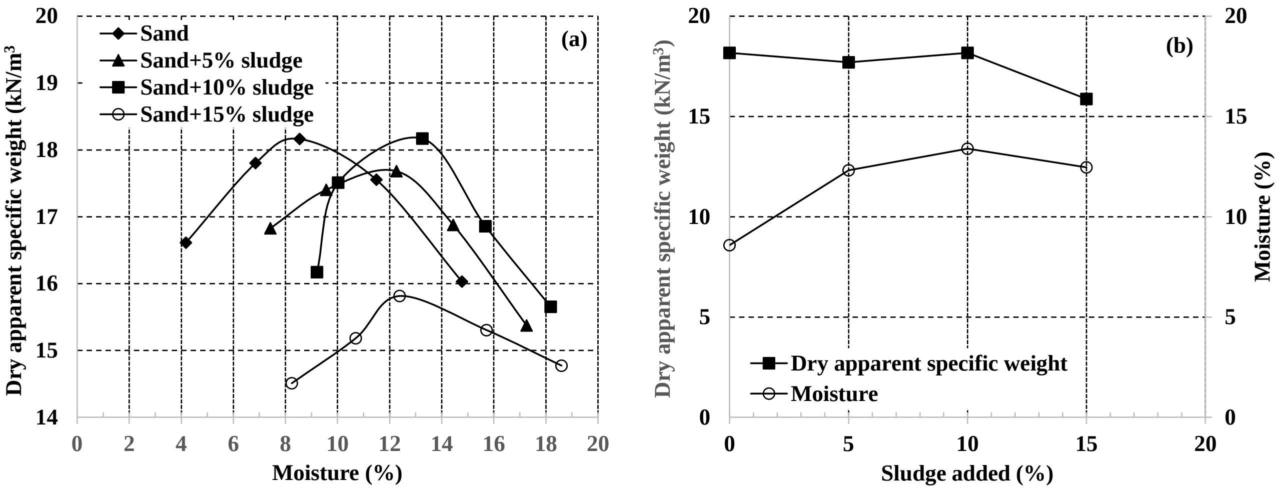

Figure 5. (**a**) Compaction curves of the tested materials and (**b**) Percent sludge versus maximum apparent dry specific weight and versus optimum moisture content.

The results of the hydraulic conductivity of the saturated natural soil were 3.6×10^{-5} m/s. This is a typical hydraulic conductivity value for sandy soils [34]. However, it was possible to observe a reduction in the hydraulic conductivity to 2.0×10^{-5} m/s with an increase in the confining stress to 200 kPa.

3.2. Chemical Characterization of Soil, Sludge, and Mixtures of Soil and Sludge

The chemical characterization of the natural soil showed that it was an acidic one (pH < 7). The pH value in potassium chloride (pHKCl) was lower than the pH value in water (pHH_2O). The pH variation ($\Delta pH = pHKCl - pHH_2O$), resulted, consequently, in a negative number, which indicates the presence of silicate clays [35]. The amount of organic matter obtained from the organic carbon is low (lesser than 1.0%), as the cation exchange capacity (T = CTC < 27 $cmolckg^{-1}$) also indicates the predominance of the clay mineral kaolinite. Base saturation was less than 50% in the case of the dystrophic soil. The percentage of sodium in the exchangeable complex (100 $Na^{+}T^{-1}$) is low (2.3%), i.e., lesser than 6%. The electrical conductivity of the saturation extract showed to be high (10 mS/cm/25 °C), i.e., greater than 4 mS/cm/25 °C. The mixtures resulting from the addition of sludge (5% to 15%) to the soil have, practically, a neutral pH, although the organic matter content presented some growth but it is still low. The cation exchange capacity (CEC) increased and the mixtures with a sludge content equal to or greater than 10% presented high CEC values (CEC > 27 $cmolckg^{-1}$). Finally, aluminum and sodium saturation decreased and the amount of water and the electrical conductivity in the saturated extract increased with the increase in sludge in the soil (Table 3).

Table 3. Chemical characterization of soil, sludge, and soil–sludge mixture.

Properties	Soil	Sludge	Soil—Sludge Mixture		
			5%	10%	15%
pH in water	6.08	7.22	6.9	7.01	7.13
pH in KCl	6.00	7.30	7.06	7.15	7.18
Organic carbon (g/kg)	1.07	14.29	8.60	9.67	11.46
Organic matter (g/kg))	1.85	24.64	14.82	16.67	19.76
Mg^{2+} exchangeable (cmol/kg)	3.30	11.00	3.00	0.20	1.50
Na^{+} exchangeable (cmol/kg)	0.30	185.80	10.40	22.30	26.90
K^{+} exchangeable (cmol/kg)	0.20	18.40	1.30	1.90	2.20
H^{+} + Al^{3+} extracted (cmol/kg)	8.10	8.90	6.01	6.67	7.37
H^{+} exchangeable (cmol/kg)	7.70	8.80	5.71	6.27	6.95
Value of V (% Sat. of Base)	0.38	0.97	0.76	0.83	0.86
% Fe_2O_3 in Ext. Sulfuric (g/kg)	0.50	2.25	0.63	0.75	0.88
% Al_2O_3 in Ext. Sulfuric (g/kg)	1.50	3.30	1.50	3.20	3.40
Electrical conductivity (mS/cm at 25 °C)	10	9769	2708	3670	5940
Specific surface (m^2/g)	18.40	14.70	3.70	11.00	11.00

3.3. Oedometer Tests

The results of the single oedometer tests performed for a dry apparent specific weight of 15.0 kN/m^3 and 17.0 kN/m^3 are shown in Figures 6–9 and Table 4. The values of the initial physical indices of the samples for each set of specimens were similar, indicating that the compaction process and the moisture control were the most suitable, with dry and wet apparent specific weights very close to those desired. The values of the collapse (*CP*) or expansion potentials (*EP*), calculated using Equation (1), for the vertical flood stresses of 10, 20, 40, 80, 160, 320, and 640 kPa in the samples compressed at the dry apparent specific weights of 15.0 kN/m^3 and 17.0 kN/m^3, are shown Figure 10.

$$CP \text{ or } EP\ (\%) = 100\Delta h/hi \quad (1)$$

where Δh is the height variation of the test body due to flooding (mm) and hi is the height of the test body before the flood.

Table 4. Collapse potential of simple oedometer tests.

Vertical Flood Stress (kPa)	Collapse Potential—CP (%)							
	Dry Specific Weight—15.0 kN/m^3				Dry Specific Weight—17.0 kN/m^3			
	0% Sludge	5% Sludge	10% Sludge	15% Sludge	0% Sludge	5% Sludge	10% Sludge	15% Sludge
10	0.11	0.13	−0.49	−0.92	0.11	−0.11	−0.37	−1.12
20	0.50	0.16	−0.06	−0.04	0.41	−0.05	−0.29	−0.60
40	1.30	0.40	0.52	0.05	0.45	0.32	0.02	−0.31
80	3.75	1.30	1.03	0.29	0.61	0.49	0.76	0.65
160	4.99	2.15	1.30	0.80	0.63	0.63	0.78	1.26
320	6.61	4.50	1.96	1.67	0.88	0.53	0.79	1.61
640	5.81	5.45	2.81	2.53	1.64	0.41	1.08	2.21

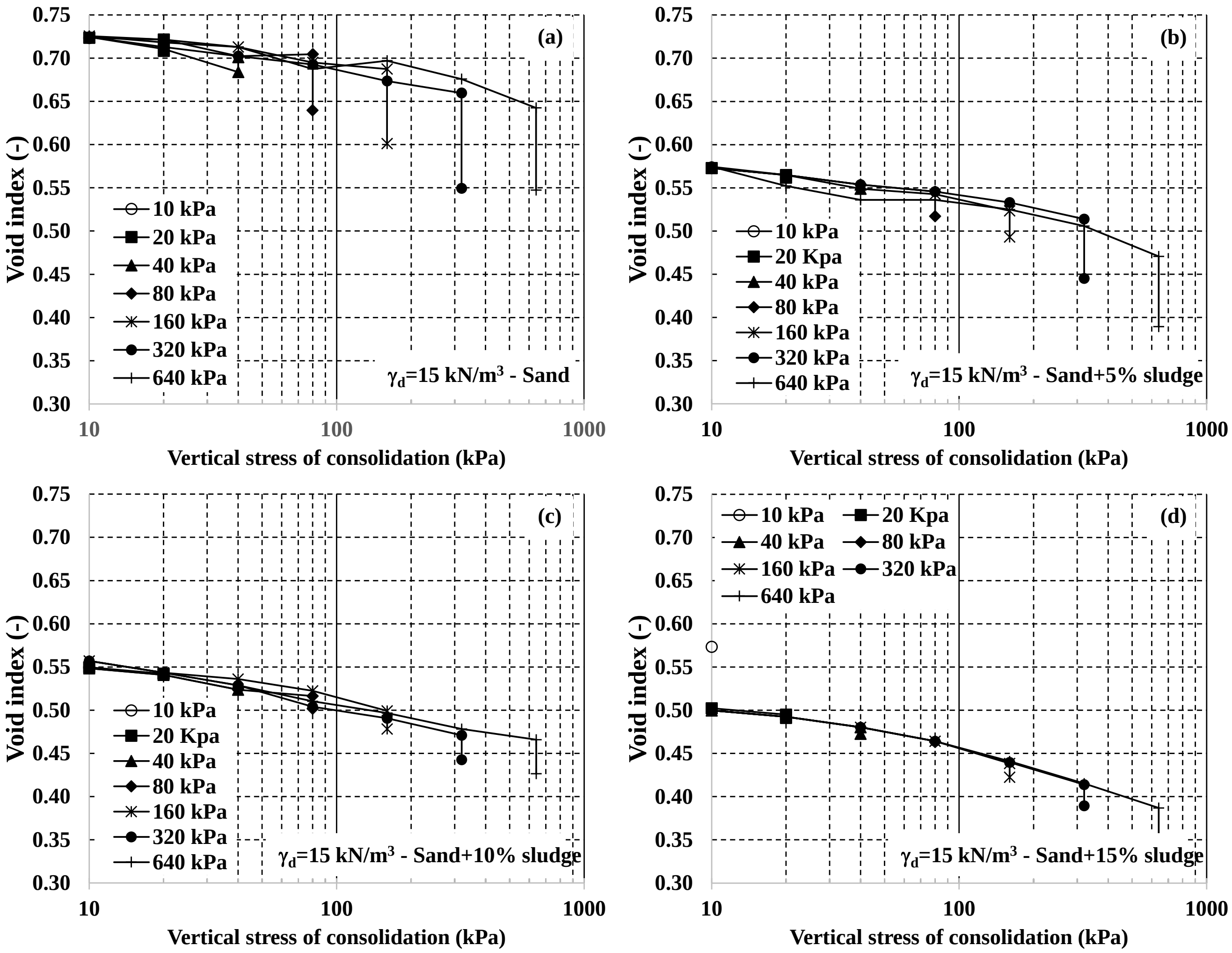

Figure 6. Variation of the void index with the vertical stress of consolidation obtained through single oedometer tests, for dry apparent specific weight of 15.0 kN/m^3: (**a**) sand, (**b**) sand plus 5% sewage sludge, (**c**) sand plus 10% sludge, (**d**) sand plus 15% sludge.

The results showed that for the soil without sludge and for a dry apparent specific weight of 15.0 kN/m^3, the collapse increased reaching a maximum value of 6.61% at a stress of 320 kPa (critical stress for maximum collapse) and then it decreased. Soil compaction for the dry apparent specific weight of 17.0 kN/m^3 significantly reduced the collapse potentials to the maximum values of 1.64% for the 640 kPa stress. The addition of sludge to the soil decreased the potential for collapse. For the dry apparent specific weight of 15.0 kN/m^3 and stress of 10 kPa, the mixtures with 10% and 15% of sludge presented a small expansion. Similar behavior was observed for the dry apparent specific weight of 17.0 kN/m^3 at the stresses of 10 kPa and 20 kPa, for mixtures with 10% and 15% of sludge.

This experimental campaign showed that the addition of sewage sludge to the soil is an important factor in reducing soil collapsibility. Similar behavior was observed with the increase in the dry apparent specific weight. For example, in the case of the dry apparent specific weight of 15.0 kN/m^3, the decrease in collapsibility of the mixtures with 5%, 10%, and 15%, compared to the natural soil was 6.2%, 51.6%, and 56.4%, respectively.

Similar results were found by Atarodi [36] when adding 0%, 2%, 4%, and 8% of sewage sludge ash and sewage sludge/lime ash to the collapsible soil of Iran. Sewage sludge samples collected from the Ikbatan wastewater treatment plant, in Tehran, were added to the collapsible soil causing reduced soil cohesion and a decreased internal friction angle ϕ [37].

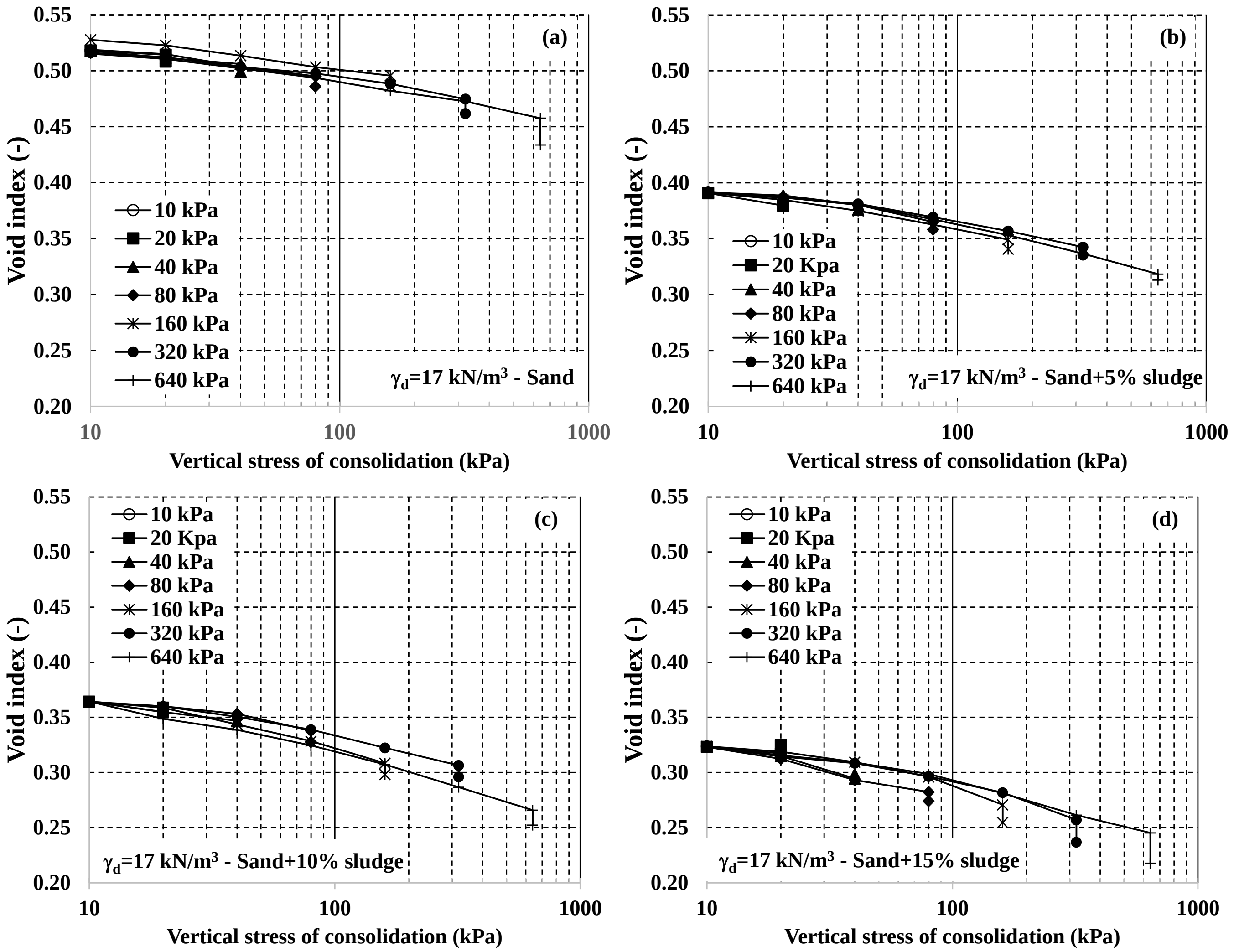

Figure 7. Variation of the void index with the vertical stress of consolidation obtained through single oedometer tests, for dry apparent specific weight of 17.0 kN/m^3: (**a**) sand, (**b**) sand plus 5% sewage sludge, (**c**) sand plus 10% sludge, (**d**) sand plus 15% sludge.

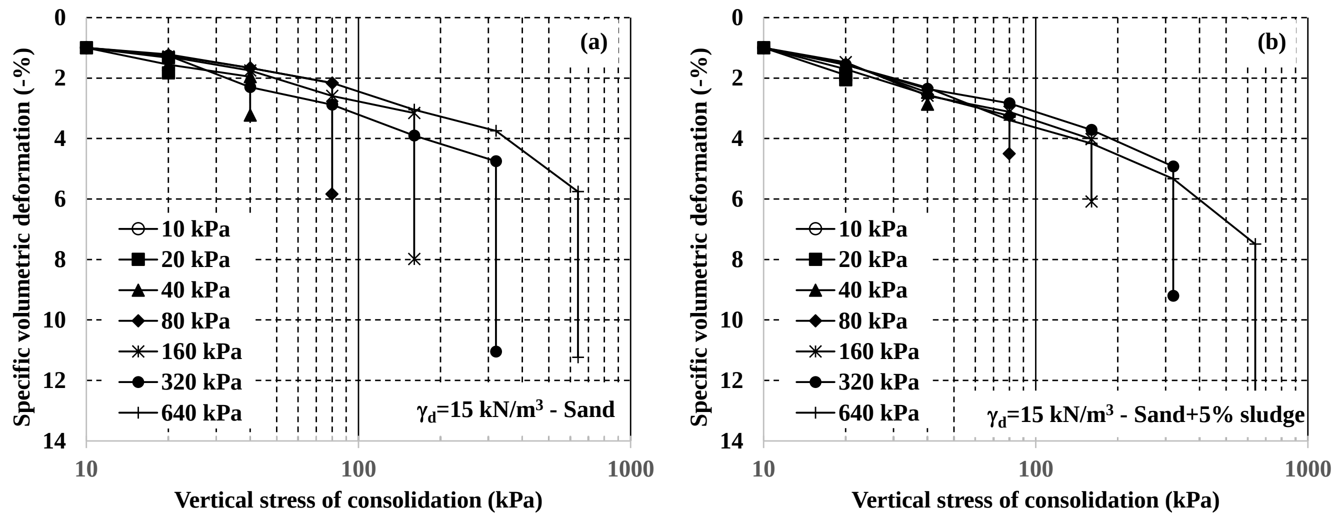

Figure 8. *Cont.*

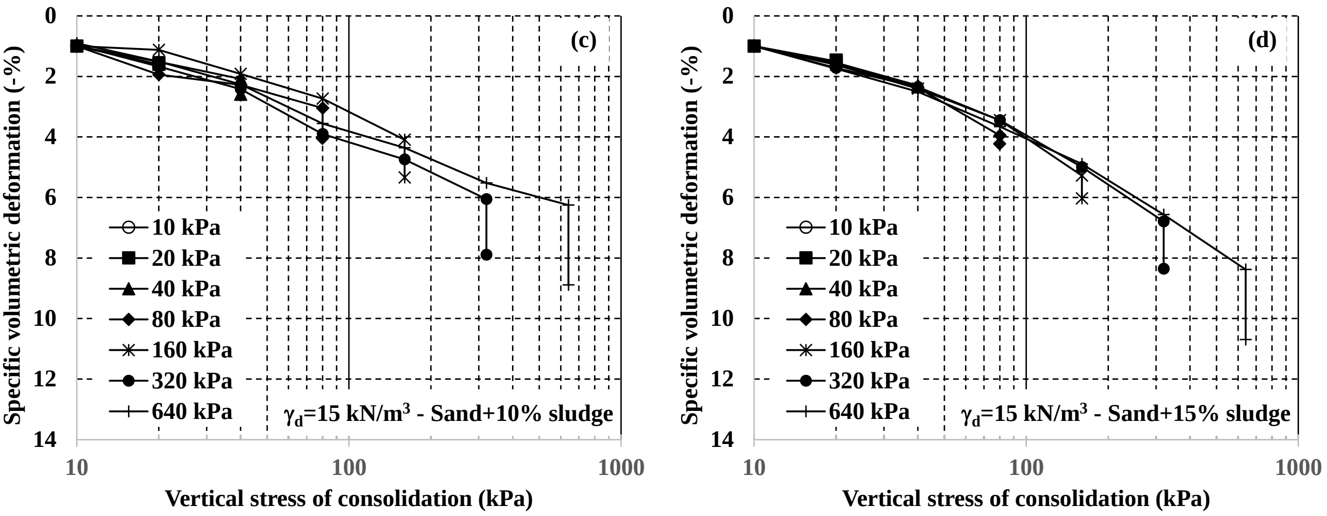

Figure 8. Variation of specific volumetric deformation with the vertical consolidation stress obtained through single oedometer tests, for dry apparent specific weight of 15.0 kN/m^3: (**a**) sand, (**b**) sand plus 5% sewage sludge, (**c**) sand plus 10% sludge, (**d**) sand plus 15% sludge.

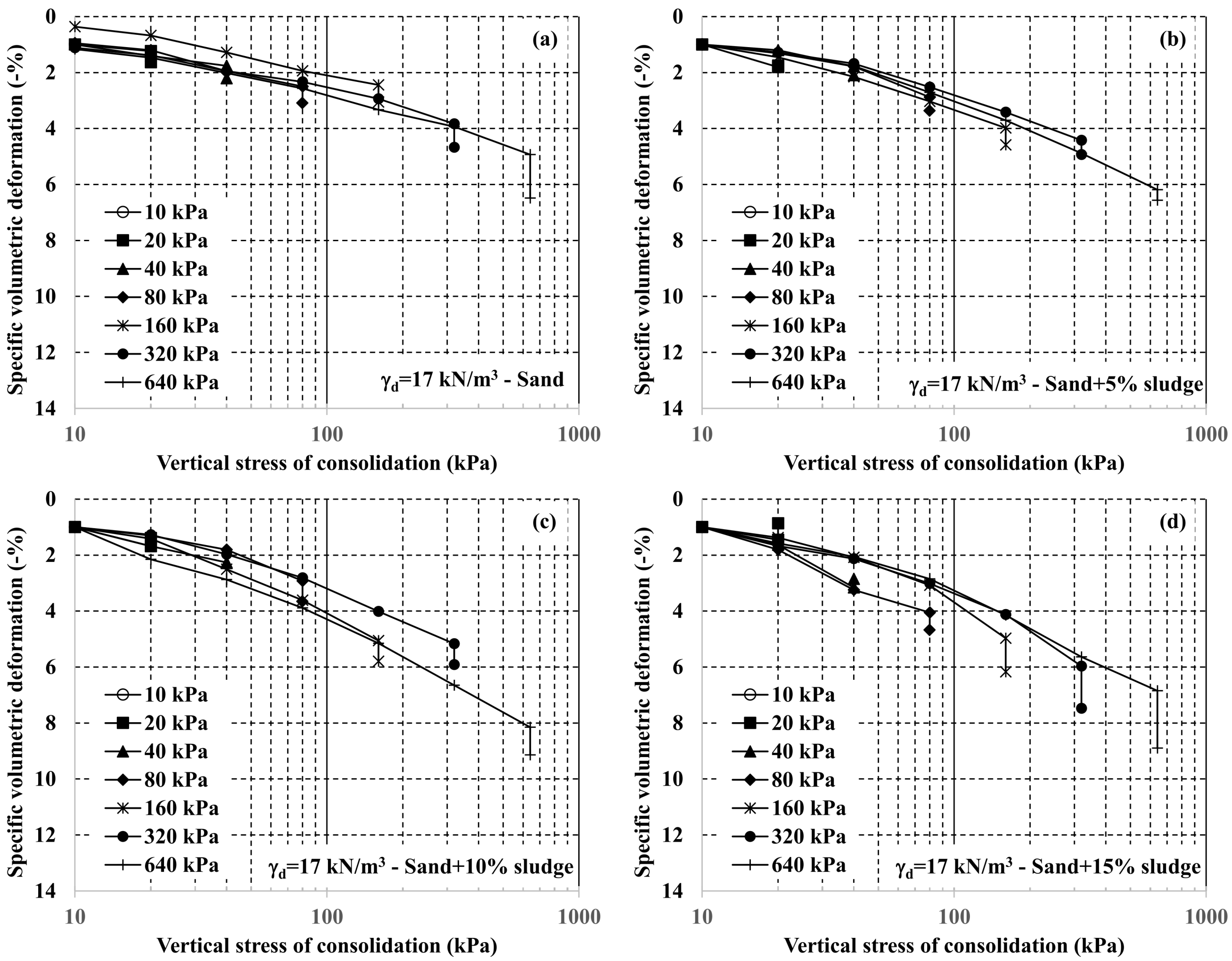

Figure 9. Variation of specific volumetric deformation with the vertical consolidation stress obtained through single oedometer tests, for dry apparent specific weight of 17.0 kN/m^3: (**a**) sand, (**b**) sand plus 5% sewage sludge, (**c**) sand plus 10% sludge, (**d**) sand plus 15% sludge.

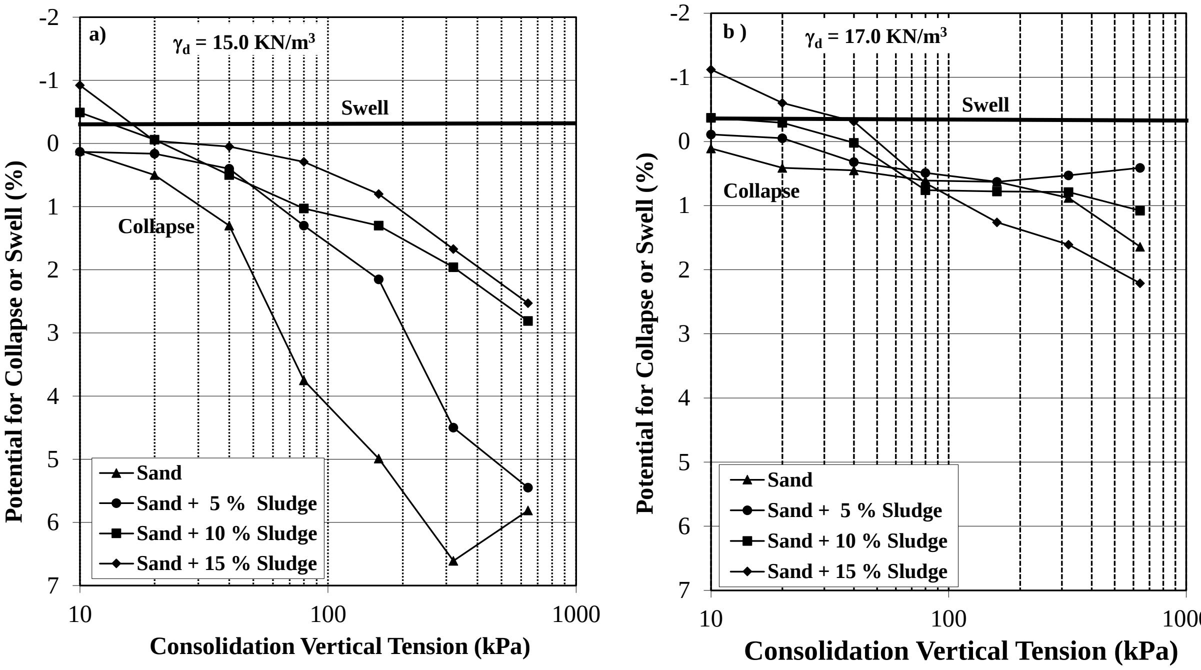

Figure 10. Variation of collapse or expansion potential values with vertical consolidation stress, (**a**) for γ_d = 15.0 kN/m^3 and (**b**) for γ_d = 17.0 kN/m^3.

Figure 11 shows, for the dry apparent specific weights of 15.0 kN/m^3 and 17.00 kN/m^3, the average values, in volume, of each component of the mixtures that was analyzed. It was possible to observe, that for the same dry apparent specific weight, the addition of sludge increased the volume of solid particles and decreased the volume of voids, due to the reduction in the air volume.

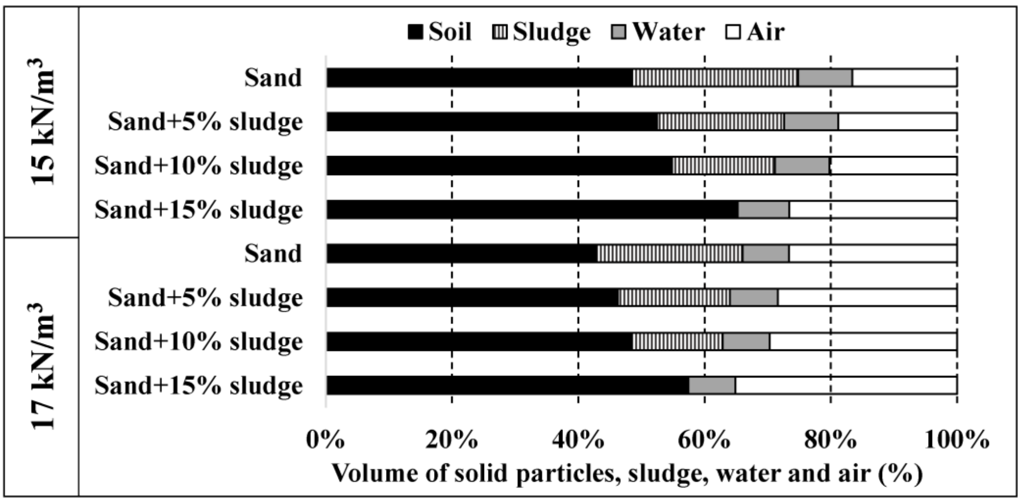

Figure 11. Volume, in %, of the different mixture components.

On the other hand, the increase in the volume of the soil particles in the mixtures, in relation to the natural soil, was significantly influenced by the difference in the actual dry apparent specific weight of the soil grains (26.16 kN/m^3), when compared to the sludge (16.27 kN/m^3). Therefore, for the same dry apparent specific weight, it was possible to observe that the addition of sludge to the soil contributed to the increase in the number of particles in the contacts between the grains. This fact produced decreases in the pore volumes, which provides greater stability to the soil structure and produced decreases in the collapsibility when the soil is flooded (Figure 12).

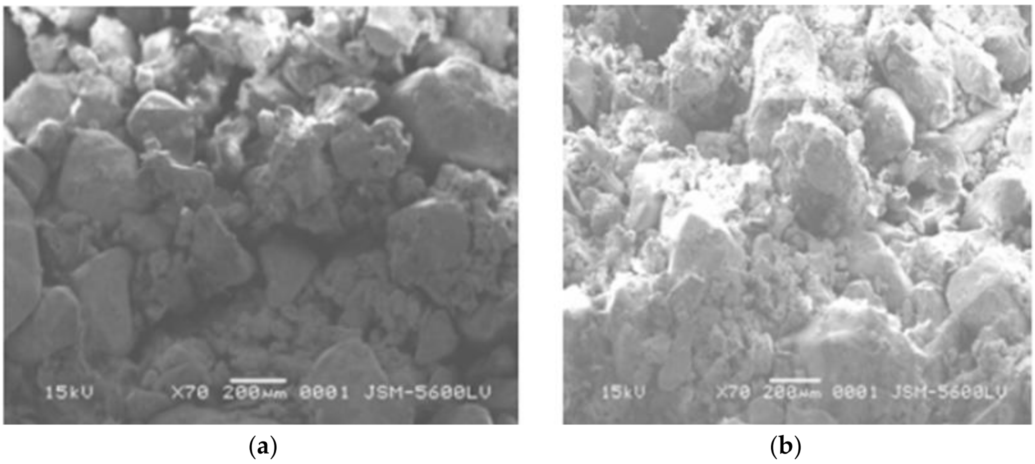

Figure 12. Electron microscopy of (**a**) natural soil—packaging, and (**b**) soil–sludge mixture—Quartz grains bonded with silts, clays, and soil–sludge organic matter.

Finally, double oedometer tests were carried out with soil and soil–sludge mixtures compacted with a dry specific weight of 15.0 kN/m^3 and 17.0 kN/m^3. Figures 13–16 present the void index versus the vertical consolidation stress, and the specific volumetric strain versus the vertical consolidation stress, obtained in tests on soil samples in natural (constant) and flooded soils (using distilled water as flood liquid).

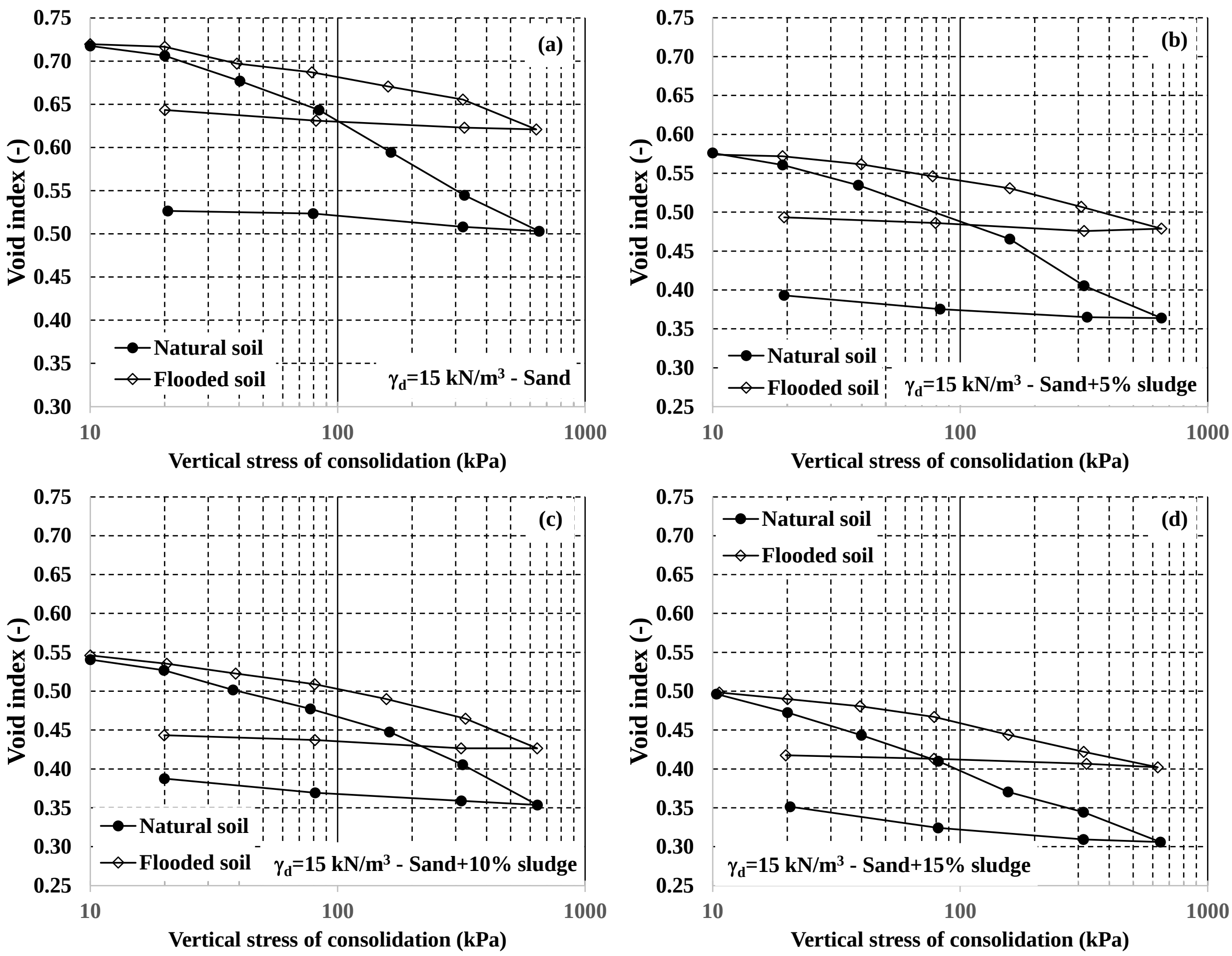

Figure 13. Variation of the void index with the vertical stress of consolidation obtained through double oedometer tests, for dry apparent specific weight of 15.0 kN/m^3: (**a**) sand, (**b**) sand plus 5% sewage sludge, (**c**) sand plus 10% sludge, (**d**) sand plus 15% sludge.

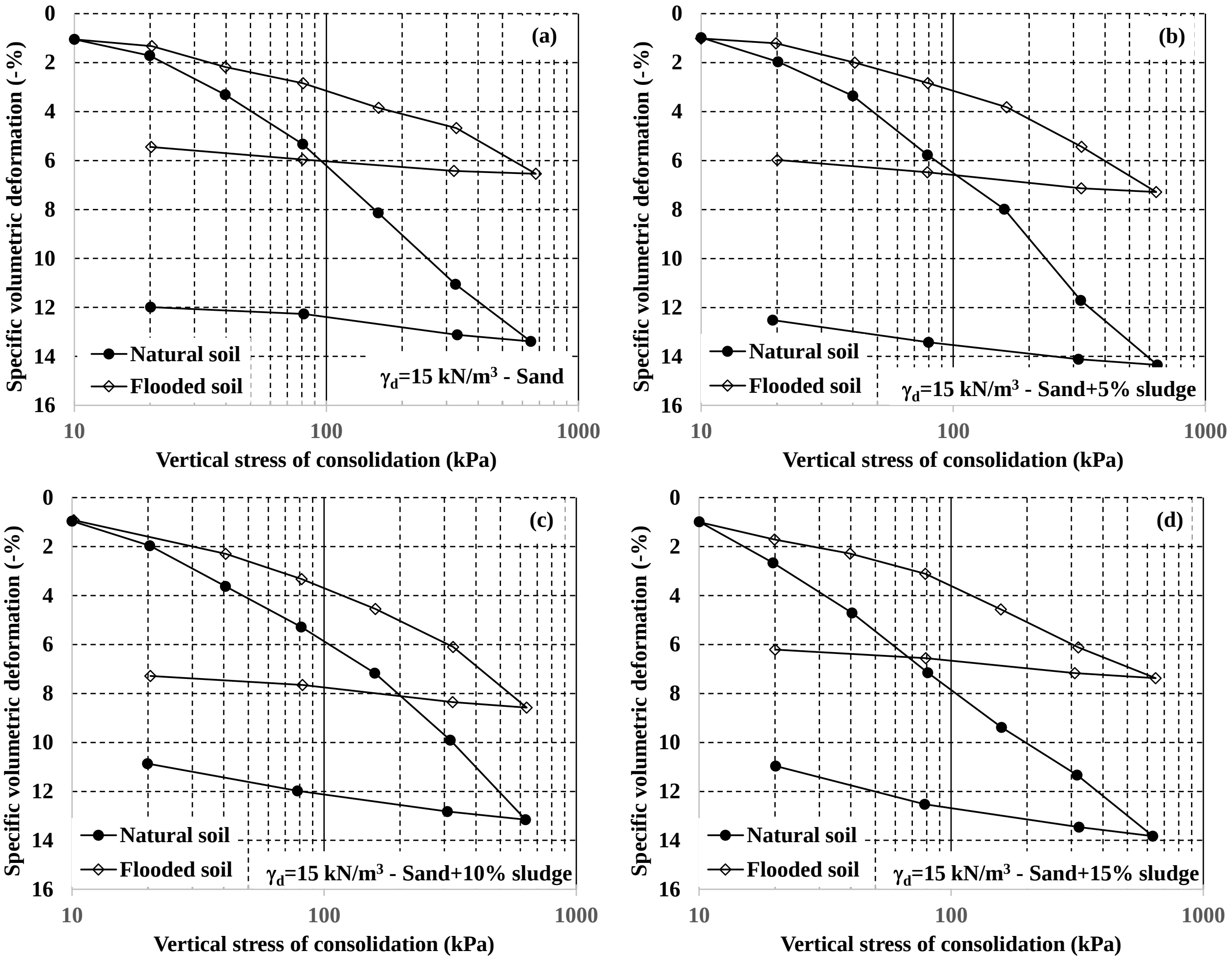

Figure 14. Variation of the void index with the vertical stress of consolidation obtained through double oedometer tests, for dry apparent specific weight of 17.0 kN/m^3: (**a**) sand, (**b**) sand plus 5% sewage sludge, (**c**) sand plus 10% sludge, (**d**) sand plus 15% sludge.

The results of the double oedometer tests, namely, the compression indexes, expansion index, and pre-consolidation stresses of the soil and soil–sludge mixtures are presented in Tables 5 and 6. It is possible to observe that the parameters obtained from the tests with natural soil presented lower values than those obtained with flooded soil samples. For the dry specific weight of 15.0 kN/m^3, the compressibility in the natural and flooded conditions increased with the addition of sludge up to 5% and then decreased with more sludge additions.

Table 5. Coefficients and parameters of the double oedometer tests with soil samples and soil–sludge mixtures with a dry specific weight of 15.0 kN/m^3.

Samples	Test Type	Coefficients and Parameters			
		Compression Index	Vertical Stress Range (kPa)	Expansion Index	Compression Index
Sand + 0% sludge	Natural	0.046	10–80	0.015	115.61
		0.055	160–640		
	Flooded	0.111	10–80	0.021	73.96
		0.129	160–640		

Table 5. *Cont.*

Samples	Test Type	Coefficients and Parameters			
		Compression Index	Vertical Stress Range (kPa)	Expansion Index	Compression Index
Sand + 5% sludge	Natural	0.044	10–80	0.016	150.31
		0.090	160–640		
	Flooded	0.111	10–80	0.021	125.89
		0.165	160–640		
Sand + 10% sludge	Natural	0.040	10–80	0.018	81.85
		0.078	160–640		
	Flooded	0.091	10–80	0.021	64.82
		0.165	160–640		
Sand + 15% sludge	Natural	0.038	10–80	0.015	80
		0.071	160–640		
	Flooded	0.096	10–80	0.021	40
		0.109	160–640		

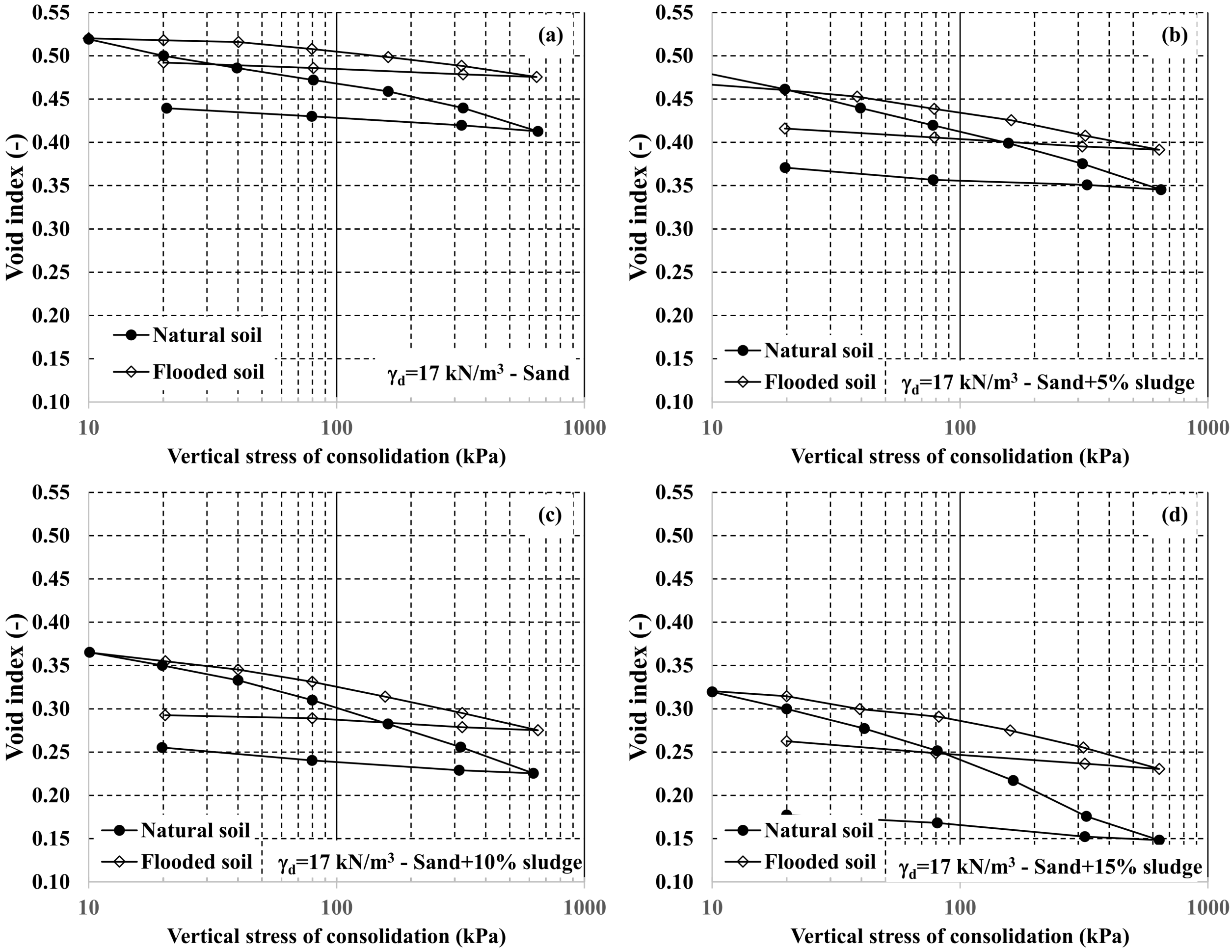

Figure 15. Variation of specific volumetric deformation with the vertical consolidation stress obtained through double oedometer tests, for dry apparent specific weight of 15.0 kN/m^3: (**a**) sand, (**b**) sand plus 5% sewage sludge, (**c**) sand plus 10% sludge, (**d**) sand plus 15% sludge.

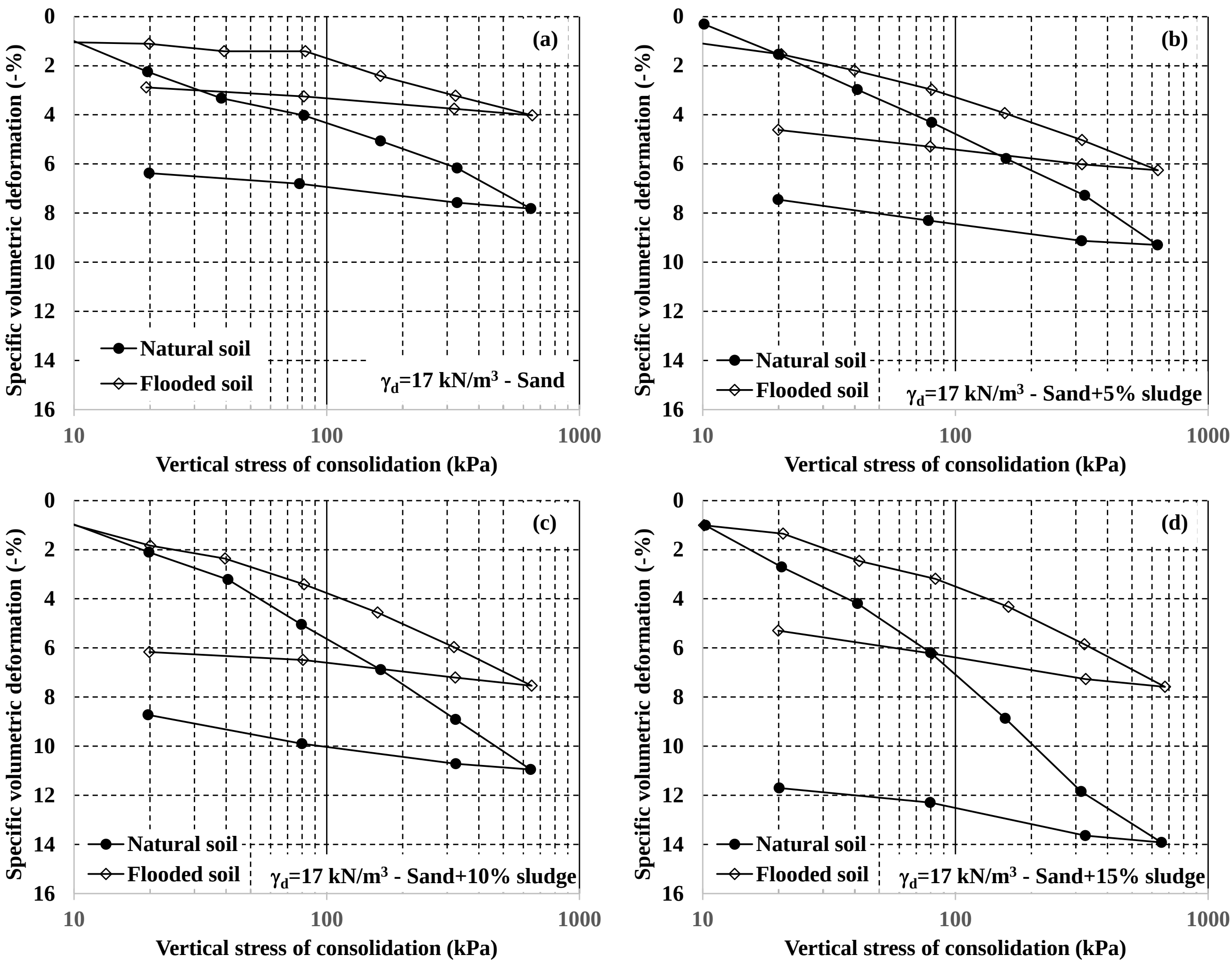

Figure 16. Variation of specific volumetric deformation with the vertical consolidation stress obtained through double oedometer tests, for dry apparent specific weight of 17.0 kN/m^3: (**a**) sand, (**b**) sand plus 5% sewage sludge, (**c**) sand plus 10% sludge, (**d**) sand plus 15% sludge.

For the dry apparent specific weight of 15.0 kN/m^3, the pre-consolidation stress in the non-flooded soil increased with the addition of sludge to the soil up to 5% and then decreased, for the higher sludge contents. In the flooded soil, the pre-consolidation stresses increased with the addition of sludge to the soil up to 10% and then decreased, for the higher sludge contents.

For the dry apparent specific weight of 15.0 kN/m^3 in the natural condition, the addition of sludge to the soil in the proportion of 5% increased the pre-consolidation stress by 30%, decreasing later for the higher levels. Similar behavior was observed in flooded conditions, with an increase in the pre-consolidation stress of about 70% for the 5% sludge addition, while decreasing with the proportions of 10% and 15% of the sludge addition.

It could also be observed that, with the dry specific weight of 17.0 kN/m^3, the parameters obtained from the tests in natural moisture were lower than those obtained from the flooded tests. With a dry specific weight of 17.0 kN/m^3, the compressibility increased with the increase in the amount of sludge, both in the natural and flooded conditions. The addition of sludge in the natural condition reduced the pre-consolidation stress by 13%, 20%, and 14% in proportions of 5%, 10%, and 15%, respectively, regarding the pre-consolidation stresses of the natural soil. In the flooded condition, it reduced the pre-consolidation stresses by 10%, 76%, and 71% in the proportions of 5%, 10%, and 15%, respectively.

Table 6. Coefficients and parameters of the double oedometer tests with soil samples and soil–sludge mixtures with a dry specific weight of 17.0 kN/m^3.

Samples	Test Type	Coefficients and Parameters			
		Compression Index	Vertical Stress Range (kPa)	Expansion Index	Pre-Consolidation Stress (kPa)
Sand + 0% sludge	Natural	0.023	10–80	0.014	147.23
		0.042	160–640		
	Flooded	0.049	10–80	0.017	231.06
		0.079	160–640		
Sand + 5% sludge	Natural	0.035	10–80	0.015	128.33
		0.057	160–640		
	Flooded	0.070	10–80	0.018	207.49
		0.089	160–640		
Sand + 10% sludge	Natural	0.039	10–80	0.016	118.23
		0.066	160–640		
	Flooded	0.052	10–80	0.018	54.50
		0.092	160–640		
Sand + 15% sludge	Natural	0.039	10–80	0.021	126.64
		0.069	160–640		
	Flooded	0.076	10–80	0.025	66.15
		0.110	160–640		

4. Conclusions

The test results indicated that the addition of sewage sludge in natural soils contributed to changes in the physical, chemical, and microstructural properties of the natural soil, an aspect that highlights the possibility to use that material to improve collapsible soils.

On the other hand, sewage sludge cannot be considered as a single waste, since each sewage treatment plant has its own and very different characteristics, thus producing sewage sludge with different properties. This means that the sewage sludge from each treatment plant must be analyzed and treated as unique in a reuse or recycling process.

For the type of sewage sludge investigated in the study, a material with an acceptable content of heavy matter and with a grain size of almost 96% granular (with a size between 4.8 mm and 0.05 mm) and 4% with a size less than 0.05 mm, the sludge mixtures resulting from the addition of 5% to 15% sludge to the natural soil had an almost neutral pH, with an increase but still low content of organic matter. The cation exchange capacity was found to increase and the mixtures with a sludge content of 10% or more had high values for the CAC compared to the other quantities studied.

In addition, it was found that aluminum and sodium saturation decreased and the amount of water and electrical conductivity in the saturated extract increased with the increase in sludge in the soil.

It should be emphasized that the increase in the sludge content, for the same specific dry weight of the soil–sludge mixture, leads to a decrease in the void content of the soil, which justifies lower collapsibility, i.e., improves the collapsibility of the soils.

Although the study focused on the investigation of the potential use of sewage sludge from Brazilian sewage treatment plants to improve collapsed soils—and this is in fact the delimitation of the research—the methodological strategy used allows its reproducibility and repeatability for other specific situations. This is possible because the methods of physical-chemical characterization of the materials used and the different mechanical tests performed—destructive and non-destructive—follow the strict recommendations of the standards of recognized quality and reliability at the national and international levels.

Based on the research conducted, which showed good prospects for the use of sewage treatment plant waste in the improvement of collapsing soils, further possibilities open up for the study of the potential uses of the material, for example, in the form of ash and possibly for the study of its pozzolanic properties.

Finally, it is important to point out that the environmental, economic, and social impacts of sewage sludge use constitute a relevant issue to be addressed as a public policy strategy for countries around the world. There is scientific evidence that the application of sewage sludge to agriculture provides a series of agronomic benefits as well as its use in land reclamation operations. Both applications exhibited confirmed environmental and economic impacts [38].

The use of sewage sludge for soil stabilization is an open and promising line of research that is part of the strategies to reduce the environmental impact of sewage treatment plant waste disposal in the environment. In fact, the total amount of sewage sludge generated in the EU27 is estimated to be about 10.13 million tons, and the main disposal routes for this material are incineration, landfilling, or structural soil amendment [38,39]. These data underline the importance of the research performed.

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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