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Enhancing Plastic Soils with Biosolid Ashes for Sustainable Geotechnical Applications: Experimental Insights from Tarija

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Abstract

This study presents a sustainable and eco-friendly methodology to enhance the physico-mechanical properties of fine-grained soils through the incorporation of biosolid ashes (BA) derived from the San Blas Wastewater Treatment Plant in Tarija. Currently, this approach provides an alternative for the reuse of more than 3,500 tons of sludge per year, a figure expected to increase significantly with the planned operation of the plant on the left bank of the Río Guadalquivir. The methodology not only improves the mechanical performance of local silt-clay soils but also promotes the valorization of residual sludge, aligning with circular economic principles and reducing the environmental impacts associated with conventional waste disposal. The biosolids were subjected to controlled incineration at 900–1000 °C, generating ashes with a specific gravity of up to 2.52, which were then incorporated into soils at dosages ranging from 5% to 30%. Comprehensive laboratory testing included Atterberg limits, moisture content, specific gravity, modified Proctor tests for maximum and optimum dry density, consolidation, direct shear, and CBR tests on both natural soils and treated mixtures. Results demonstrated reductions in plasticity index of up to 9.5%, substantial increases in shear strength and bearing capacity, and compressibility reductions of up to 45%. CBR strength improved by more than 100% for mixtures containing 30% BA, with optimal performance observed at 10–15% BA content (average specific gravity 2.40). These findings confirm that biosolid ashes are an effective and environmentally responsible additive for geotechnical soil stabilization, offering a sustainable solution that simultaneously addresses construction requirements and promotes ecological waste management in Tarija.

Keywords: plastic soils; sewage sludge ash (SSA); physical and mechanical properties of soils; soil–ash interactions; sustainable soil improvement

1. Introduction

By 2030, an estimated 2.1 billion additional people will be living in cities [1,2]. This growth increases the demand for wastewater treatment, a process in which sewage sludge is generated by removing suspended solids and converting soluble organic matter into bacterial biomass [2].

Bianchini et al. [3] describe sewage sludge (SS) as a mixture of organic and inorganic fractions whose composition is strongly influenced by the type of treatment and the origin of the influent. According to Gherghel et al. [4], SS can be classified into primary sludge, resulting from the sedimentation of suspended solids; secondary sludge, consisting of the excess biomass generated in biological processes; and tertiary sludge, produced in advanced treatments aimed at removing nutrients such as nitrogen and phosphorus.

Kelessidis and Stasinakis [5], as well as Bertanza et al. [6], point out that population growth and urban expansion in recent years have driven both the proliferation of wastewater treatment plants (WWTPs) and the significant increase in the generation of residual sludge.

Furthermore, Shehu et al. [7], Pérez-Elvira et al. [8], and Sever et al. [9] indicate that stricter effluent quality requirements in wastewater treatment plants not only increase sludge production but also deteriorate its characteristics. Like other types of waste, sewage sludges must be minimized, not only to comply with directives but also because of the cost of its management [10].

On the other hand, Collivignarilli et al. [10] point out that sludge minimization technologies are usually structured in three main approaches: (i) decrease in sludge production; (ii) reduction of its water content through dehydration processes; and (iii) decrease in the fraction of volatile solids through stabilization stages.

Residual activated sludge generated in wastewater treatment plants is considered problematic, as it can be a significant source of secondary pollution due to the presence of various contaminants. Therefore, the development of innovative and economically viable treatment methods is essential to ensure its safe and environmentally sustainable management [11].

Raheem et al. [11] describe various routes for the disposal, volume reduction, or energy recovery of sewage sludge, including anaerobic digestion, incineration, pyrolysis, gasification, and enhanced digestion processes assisted by fuel cells. However, Fuerhacker and Haile [12] point out that one of the most widespread and recommended alternatives remains the application of sewage sludge to soil. Nevertheless, this option faces growing concern globally due to the presence of organic contaminants and the debate surrounding the need for stricter regulations.

Nguyen et al. [13] states that reduced access to landfills, increased disposal costs, and the zero-waste concept are driving different approaches to sludge management and disposal. The principles of the Circular Economy, which promote regenerative design, waste reduction, and the continuous use of resources, are becoming increasingly important for water authorities.

Nguyen et al. [13] also points out that the analysis of the general properties of sludge and current disposal and sustainable management practices are alternatives that allow for reuse, recycling and recovery options with social, economic and environmental approaches.

Vouk et al. [14] proposes the reuse of sewage sludge or its treatment byproducts using ash. The incineration process of sewage sludge generates a special type of ash, the volume of which is three to five times smaller than that of stabilized and dewatered sludge.

In their research, Vouk et al. [14] proposes, for example, that the ash from wastewater sludge can be used in cement mortars, highlighting its significant potential for incorporation into the concrete industry.

According to Kumar et al. [15], biosolids are sewage sludge and are generated as a byproduct of municipal wastewater, sewage effluents, and wastewater treatment plants. Treatment plants generate a large quantity of biosolids. Biosolids can have various applications, such as biogas production, landfill, organic fertilization, soil amendment, and improving agricultural crop yields. However, Kumar et al. [15] points out that, due to their high content of heavy metals and microorganisms, their applications may be limited if pretreatment is not carried out.

In this same respect, Smith, S. [16] asserts that organic chemicals discharged in wastewater or those that enter by atmospheric deposition in paved areas concentrate in sewage sludge, with possible implications for the agricultural use of sludge as soil improvers.

According to Krüger et al. [17], sludge incineration degrades organic compounds almost completely but concentrates heavy metals and phosphorus. However, sewage sludge ash almost eliminates all the compounds that limit the use of biosolids.

Current options for biosolids management are diverse; however, sludge incineration is a promising technology. Incineration is attractive for both volume reduction and energy recovery. Emissions reported from biosolids incineration were compared with various regulations to identify challenges and future directions for biosolids incineration research [18].

Roy et al. [18] points out that most of the gaseous and metallic emissions generated during incineration were lower than those established by current regulations or could be offset by existing technologies.

Several researchers, such as Lin et al. [19], Arulrajah et al. [20,21], and Tastan et al. [22], point out that biosolids and ash are widely used in various engineering fields. However, stabilization of these materials is necessary due to the wide variation in their properties and the need to improve them to make them suitable for civil engineering applications.

Wanare et al. [23] analyzes the various uses of biosolids and their ash. They note that the water content of biosolids is usually less than 80%, although some studies have reported values exceeding 200%. The organic content can reach up to 28%. The maximum dry density varies between 7.5 and 8.5 g/cm^3, and the optimum water content is between 50 and 76%, showing considerable variability. Therefore, it is necessary to apply appropriate stabilization methods to ensure optimal use in engineering.

Kumar et al. [15] notes that the application of sewage sludge is very productive for the yield of agricultural crops.

Franz, M. [24], states that sewage sludge incineration results in a high phosphorus content, ranging from 4% to 9%, and that approximately 90% of the phosphorus can be extracted from the sewage sludge ash to produce a suitable phosphate fertilizer. He also notes that approximately 37% of the sewage sludge produced is applied to agricultural land. Fytili et al. [25] indicate that other major uses include land reclamation and restoration (12%) and incineration (11%).

For their part, Lundin et al. [26] in their research concluded that two sludge management options, incineration and direct application to agricultural soil, however, these alternatives present economic and environmental restrictions, respectively.

The Environmental Protection Agency (EPA) [27,28] notes that sewage sludge can be processed using various methods to reduce pathogens. The most important methods are aerobic digestion, air drying, anaerobic digestion, composting, and lime stabilization. In the air-drying method, the sludge is dried for months or longer in sand drying beds or paved tanks.

Walker, J. [29], demonstrates that sewage sludge can be used for soil applications, and for this purpose, the wastewater treatment plant must transform it into biosolids. Liang et al. [30] and Tejada et al. [31], demonstrate that the application of biosolids increases the microbial biomass of the soil and some enzymatic activities, such as urease, alkaline phosphatase and β-glucosidase, linked to the C, N, P and S cycles of the soil.

Liang et al. [32] also propose that the incorporation of organic amendments into the soil stimulates dehydrogenase activity, since the added material may contain intracellular and extracellular enzymes, and may also stimulate microbial activity in the soil.

For their part, Tejada et al. [31] and Walker, J. & Bernal, M. [33] found that compost or sewage sludge were effective for the remediation of saline soil. Abdelbasset et al. [34] reports that the use of compost from municipal solid waste (13.3 g kg-1) and sewage sludge (26.6 g kg-1) significantly improves the physicochemical properties of the soil, especially the carbon and nitrogen content.

Donatello and Cheeseman [35] point out that Portland cement mainly contains calcium, silica, aluminum, and iron, elements that are also found in the ash of waste sludge. Husillos et al. [36] propose using this sludge in clinker production, taking advantage of its calorific value when dry.

Jamshidi et al. [37], Donatello, S. & Cheeseman, C. [35], Monzo et al. [38,39], Pan et al. [40], Cyr et al. [41] and Garces et al. [42], published that the partial substitution of Portland cement by biosolids ash influences the workability and strength of cement pastes, mortars or concrete. The considerable content of SiO_2 and Al_2O_3 in the residual sludge ash guarantees its use as a pozzolanic material [35].

Regarding concrete strength, Pan et al. [40], Paya et al. [43], and Tay et al. [44] show considerable differences. For example, replacing 20% of Portland cement with biosolids ash results in varying reductions in compressive strength.

In another investigation, Jamshidi et al. [37] states that replacing 10% of cement with biosolids ash causes an 8% reduction in compressive strength.

Kalogo and Monteith [45] propose using sewage sludge to generate and recover energy. Bachmann [46] highlights that dried sludge is a renewable source with a calorific value similar to lignite. Pöschl et al. [47] suggest converting biogas into biomethane for the natural gas grid. Halls [48] explains that anaerobic digestion stabilizes organic waste and produces biogas, composed of methane and carbon dioxide.

In the ceramic industry, the addition of residual sludge or its ash can increase porosity and reduce the density, thermal conductivity and mechanical strength of bricks [49]; however, its inclusion up to 10% allows maintaining the required strength Weng et al., [50]; Teixeira et al., [51], and biosolids ash can be used as an additive or substitute for clay or sand, Petavratzi & Wilson, [52]; Anderson & Skerratt, [53].

Al-Sharif, M. & Attom, M. [54], demonstrate that, by incorporating biosolids ash into soft and cohesive soils, these improve in stabilization by decreasing the soil plasticity index.

Lin et al. [55] and Chen [56] show that incorporating up to 7.5% biosolids ash increases the maximum dry density of the soil, reduces its swelling potential and improves its basic properties; in addition, stabilization with ash decreases the plasticity index, improving the bearing capacity of soft foundation soil.

Sato et al. [57] have concluded that biosolids ash can be used as filler in asphalt mixtures, but that the quality of the mixtures is slightly lower than that of conventional mixtures. Lim et al. [55] demonstrate that the reduction of the liquid limit is approximately 60-65% when a significant proportion of biosolids ash has been used.

In another investigation, Maghoolpilehrood et al. [58] attribute the increase to the porosity of the biosolids and ash mixture. Furthermore, they demonstrated a reduction in the void ratio from 1.34 to 1.01 and in the consolidation coefficient from 4.8×10^2 m^2/year to 3.67×10^2 m^2/year for biosolids treated with 5% cement, compared to untreated biosolids.

Disfani, et al. [59], establishes that the application of stabilized biosolids in road embankments is a sustainable solution in geotechnical engineering applications. The application of sewage sludge ash (SSA) and hydrated lime to stabilize soft cohesive subgrade soils, in proportions of 2%, 4%, 8%, and 16%, shows increases in unconfined compressive strength and shear strength with triaxial testing, improving from 30 to 50-70 kPa. [19].

Tests conducted on clay soils with biosolids ash mixed in proportions of 10%, 15%, and 20% of the soil dry weight showed an increase in the soil's uniaxial compressive strength, while the bearing capacity decreased. A biosolids ash percentage of 10% provided the optimum CBR value [60].

Sewage sludge ash (SSA), obtained from the incineration of sewage sludge, differs significantly from fly ash/bottom ash in its chemical, physical, and cementing characteristics. Soil stabilization is essential due to the increase in construction. Several studies have demonstrated that sewage sludge ash possesses pozzolanic properties and has the potential to stabilize soft soils [61].

The combustion product of sewage sludge and its combination with sand meets all regulatory requirements for materials suitable for embankments. It reduces the breaking strength by 30% after immersion of the waste, resulting in relatively low California Bearing Ratio (CBR) values [62].

Demir, S and Cabalar, A. [63], carried out experiments on clays mixed with sewage sludge ash (SSA) in percentages of 10, 20 and 30%, demonstrating that the addition of SSA increased the estimated values of the liquid limit and the undrained shear strength of the mixtures.

Zang, et al. [64] and Han et al. [65] They point out that the mud is characterized by a high water content, low permeability, and low load-bearing capacity, which hinders its sustainable use in engineering. However, it is claimed that stabilizing and treating this mud significantly improves soil permeability and, with special methods, its shear strength can be increased, resulting in a much denser and more stable microstructure.

The Wastewater Treatment Plant (WWTP) on the right bank of the city of Tarija has been operating since 2021 and generates approximately 3,500 tons of sewage sludge annually [66], the only current reuse of which is in the agricultural sector. The planned construction of a second WWTP on the left bank will significantly increase sludge production, without a strategy yet in place for its sustainable management.

Recently, the Universidad Católica Boliviana, Tarija Campus, evaluated the use of biosolids ash as an additive in H17-type concrete [67]. Biosolids exhibit high variability in their properties—including high water and organic matter content—and therefore require prior stabilization. Incineration allows for the reduction of heavy metals and the production of ash with more stable characteristics [68].

This paper presents the results of an experimental investigation exploring the use of sewage sludge transformed into ash as a sustainable, eco-friendly, and environmentally responsible solution for geotechnical soil improvement. The study examines soil-biosolid ash mixtures in varying proportions and evaluates their impact on the physical and mechanical properties of the soil. Conducted in the city of Tarija, Bolivia, this research addresses the growing generation of sludge from wastewater treatment plants and proposes a sustainable and circular alternative for its management and valorization, contributing to ecological conservation and the development of environmentally sound engineering practices.

2. Materials and Methods

This section details the current characteristics of the waste sludge collection and handling process and describes the theory used for the experimental geotechnical process employed to determine the physical and mechanical properties of the soil in its natural state and those mixed with sludge ash.

2.1. Sampling and Study Areas

The research was conducted in the urban area of the municipality of Tarija, Bolivia. Five sampling areas of fine soil were selected, located in areas of urban expansion and characterized by the presence of plastic soils. The sludge used came from the San Blas Wastewater Treatment Plant. Figure 1 shows the soil sampling areas and the location of the treatment plant.

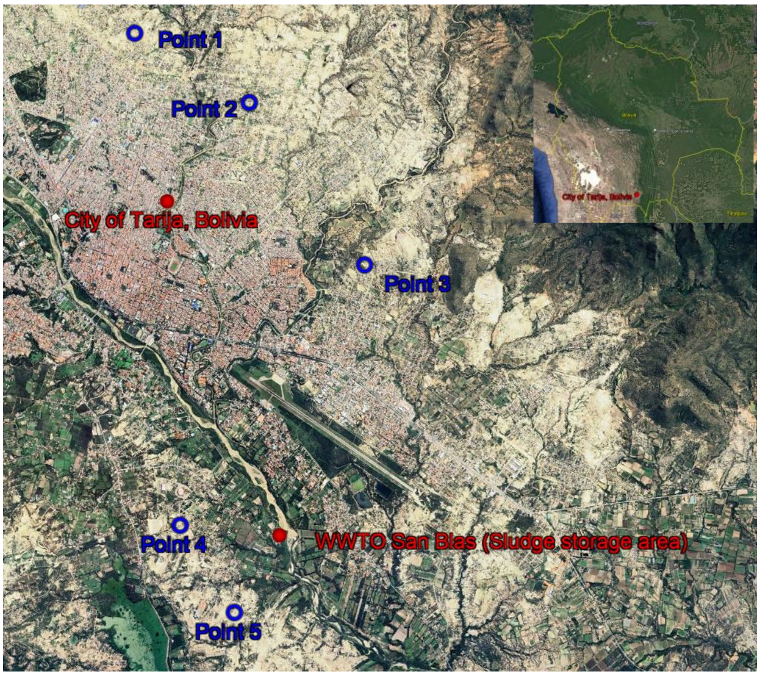

Figure 1. sampling and study areas.

2.2. Residual Sludge

The wastewater treatment plant (WWTP) located on the right bank of the city of Tarija began operations in 2021 and currently generates approximately 3,500 tons per year of sewage sludge [66], its only known use being agricultural. The sludge generated during the treatment process is initially dried and stored in the open air, from where independent agricultural producers collect it for reuse as fertilizer. Figure 2 shows the storage area and the location of the sludge within WWTP.

Figure 2. Collection and location of residual sludge.

2.3. Laboratory Test

Laboratory tests were conducted using soil samples from the study area. Sludge was obtained from the storage facilities of the San Blas Wastewater Treatment Plant (PTAR San Blas), Figure 2. Experiments were performed with conditioned soils, untreated biosolids, and previously generated biosolids ash.

The sludge samples were cured for 24 hours at room temperature (20–25 °C). Subsequently, they were oven-dried at 110 °C and finally calcined in a muffle furnace.

In detail, the trials and research included the following:

- Moisture content according to ASTM D2216-90 [69];
- Specific gravity, ASTM D854 [69];
- Ability to Work, Liquid Limit, and Plastic Limit according to ASTM D 4318 [69];
- Modified Proctor compaction tests according to ASTM D 1557-78 [69];
- Direct shear tests according to ASTM D 3080-90 [69];
- One-dimensional consolidation (primary) tests according to ASTM D2435 [70].
- CBR test according to ASTM D 1883-87 [69].

2.4. Methodology

The extracted sludge was incinerated in a Vector muffle furnace at temperatures between 800 and 900 °C. The resulting ash was ground to obtain fine particles of a size like that of the soil and characterized, determining physical properties such as specific gravity.

The soil samples were dried at room temperature and pulverized to homogenize them, following the procedures established by ASTM for each test. The natural soil was characterized by physical and mechanical tests, obtaining natural moisture content, specific gravity, consistency limits (liquid and plastic limits), internal friction and cohesion by direct shear, compressibility index by consolidation, as well as expansion and resistance through the CBR test.

Mixtures of natural soil with sludge ash were prepared in proportions of 5, 10, 15, 20, 25, and 30% by weight of the dry soil, and the same tests were subsequently performed. The results obtained allowed us to analyze and compare the properties of the natural soil against the different mixtures with sludge ash, evaluating their effect on the physical and mechanical behavior of the material.

3. Results

The results obtained during the geotechnical experimental process of fine soils and in combinations with residual sludge ash in concentrations of 5, 10, 15, 20, 25 and 30% are shown.

3.1. Sludge and Ash Assessment

The residual sludge used in this study was extracted from WWTP, presenting an initial moisture content of 70% and a specific gravity of 1.69. Incineration aimed at obtaining ash must be carried out under controlled thermal conditions and incorporating suitable gas purification systems, to minimize the emission of dioxins, furans, NOx, N_2O, SOx, HCl, HF, volatile organic compounds (VOCs) and fly ash [71–74].

For this study, the sludge was subjected to incineration processes in a muffle furnace, using different temperatures to evaluate the physical properties of the ash generated under each thermal condition. Figure 3 shows the mass reduction associated with the temperature increase, while Figure 4 shows the variations in the specific gravities of the ash obtained at each incineration level.

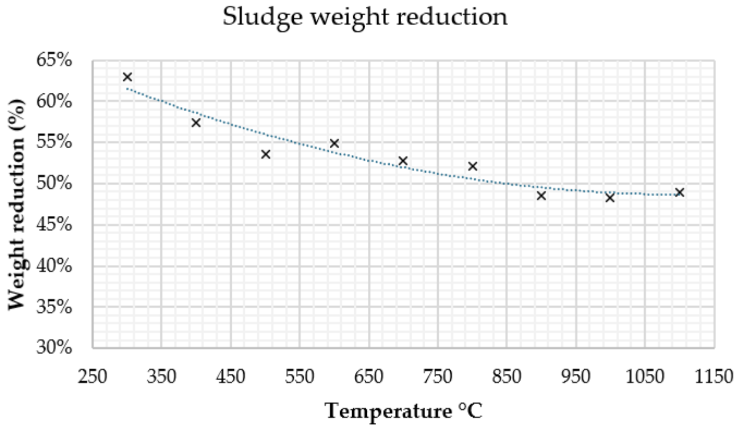

Figure 3. sludge weight reduction for each increase in incineration temperature.

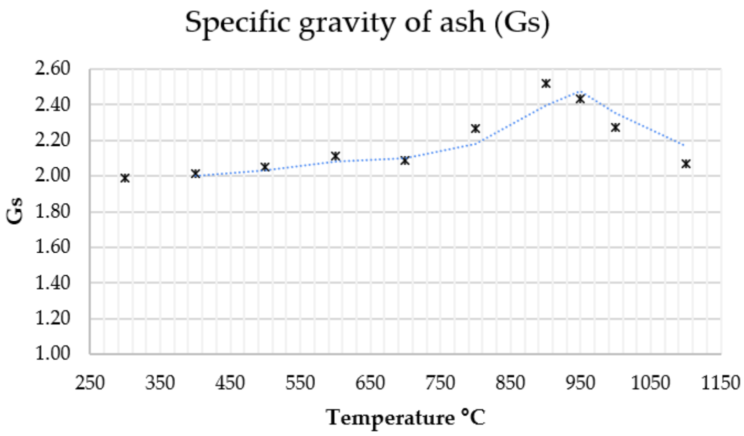

Figure 4. Specific gravity of the ashes for each incineration.

Figure 3 shows a progressive decrease in sludge mass, reducing by approximately 35% at 300 °C and reaching up to 55% at 1100 °C, confirming the high organic matter content present in the material. Figure 4 shows that the highest specific gravities are obtained when incineration is carried out at temperatures between 900 and 1000 °C. Figure 5 illustrates the appearance of the ash generated at 900 °C.

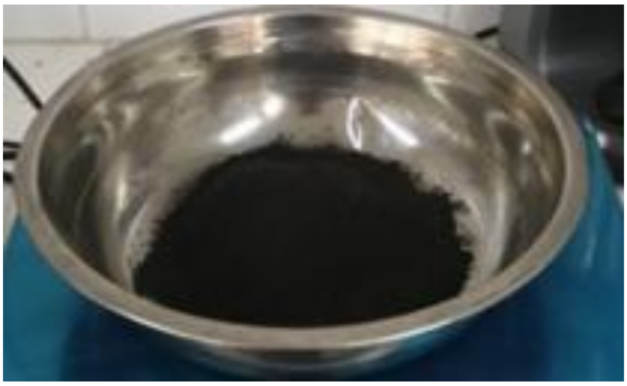

Figure 5. Ash from biosolids generated by incineration at 900 °C.

3.2. Results of Soils Combined with Biosolids Ash

3.2.1. Specific Gravity of Soil and Ash

The specific gravity of the soil was determined in its natural state and in mixtures with biosolids ash, using proportions of 5, 10, 15, 20, 25, and 30%. Table 1 and Figure 6 present the results obtained, as well as the variation in the material's behavior for each of the soil-ash combinations evaluated.

Table 1. Specific gravity of soil + biosolids ash.

Test	% ash	Gs	Decrease
1	0	2.78	0.00
2	5	2.38	-14.36
3	10	2.40	-13.55
4	15	2.41	-13.31
5	20	2.36	-15.12
6	25	2.32	-16.43
7	30	2.31	-16.91

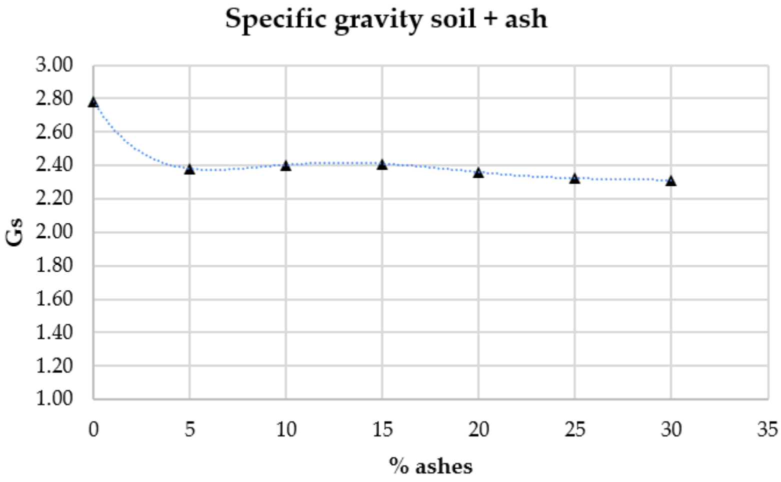

Figure 6. Specific gravity of the ashes for each incineration.

The results in Table 1 and Figure 4 show that the specific gravity of the soil in its natural state of 2.78 decreases to 17% when there is 30% ash; however, between 10 and 15% is the combination with the lowest degrees of reduction in soil density.

3.2.2. Consistency Limits: Liquid Limit and Plastic Limit

The results of the Liquid Limit and Plastic Limit for the different combinations are shown in Table 2 and Figure 7.

Table 2. Liquid Limit and Plastic Limit of soil + biosolids ash.

Soil + Ashes	LL	LP	IP
0%	36.5	25.2	11.3
5%	35.5	27.5	8
10%	34	29.5	4.5
15%	33	26.7	6.3
20%	34.3	27.3	7
25%	35	30.9	4.1
30%	36.3	28	8.3

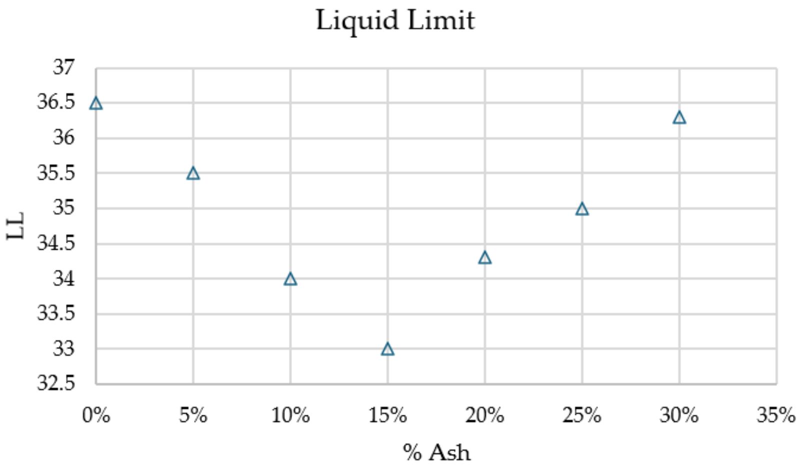

Figure 7. Liquid Limit soil + biosolids ash.

The results show a significant reduction in soil plasticity when sewage sludge ash is incorporated, with the lowest liquid limit (LL) values observed when between 10 and 15% ash is added, representing an approximate 10% decrease in plasticity. Although the plasticity chart presented in Figure 8 classifies the soil as having medium plasticity, a notable reduction in plasticity with the incorporation of sewage sludge ash is clearly evident.

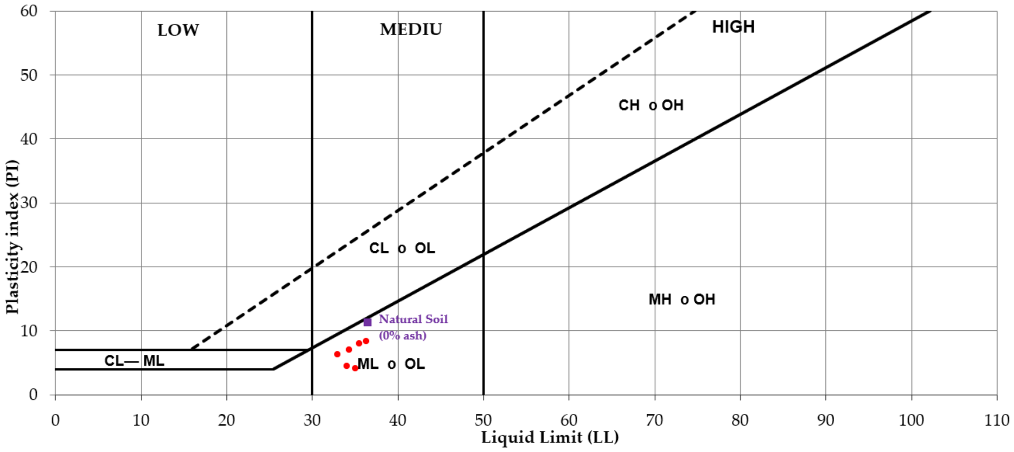

Figure 8. Plasticity chart: soil + biosolids ash.

3.2.3. Proctor T-180 Compaction

The modified Proctor T-180 compaction test was performed on both the natural soil and each of the mixtures with biosolids ash. Figure 9 shows the soil behavior as a function of water content for each combination, while Figure 10 shows the maximum densities achieved in each case.

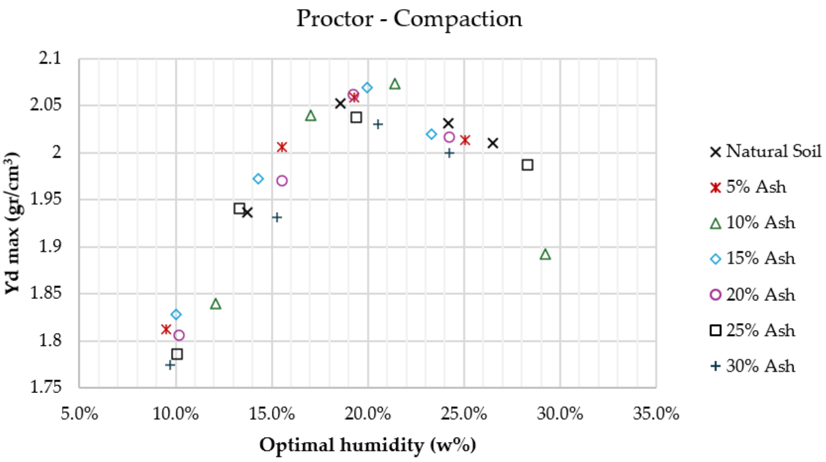

Figure 9. Proctor soil + biosolids ash.

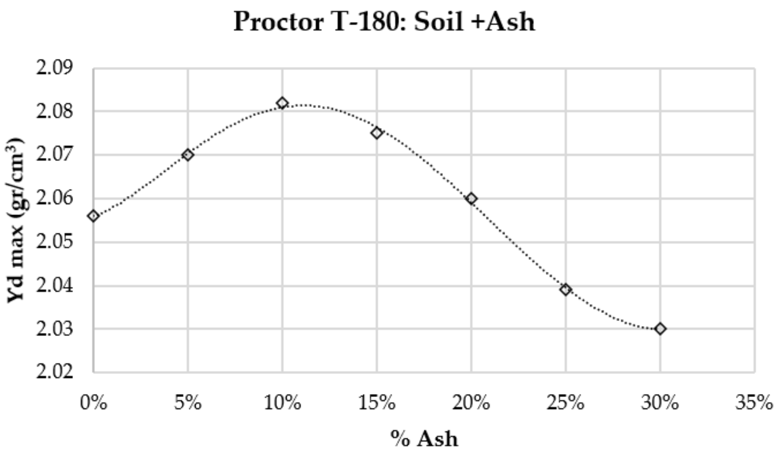

Figure 10. Maximum dry density: Proctor soil + biosolids ash.

The results indicate that maximum dry densities are achieved in soil mixtures with 10–15% sludge ash, reaching a value of 2,082 g/cm³, which represents an approximate 13% increase compared to the density of the natural soil. Figure 9 also shows that the optimum moisture content for these mixtures is close to 20%.

3.2.4. Direct Shear: Resistance Parameters

The direct shear test was carried out for the different soil mixtures with sludge ash, determining the fundamental parameters for evaluating shear strength: the angle of internal friction and cohesion. Figures 11 and 12 show the behavior of both parameters with respect to the different proportions of ash.

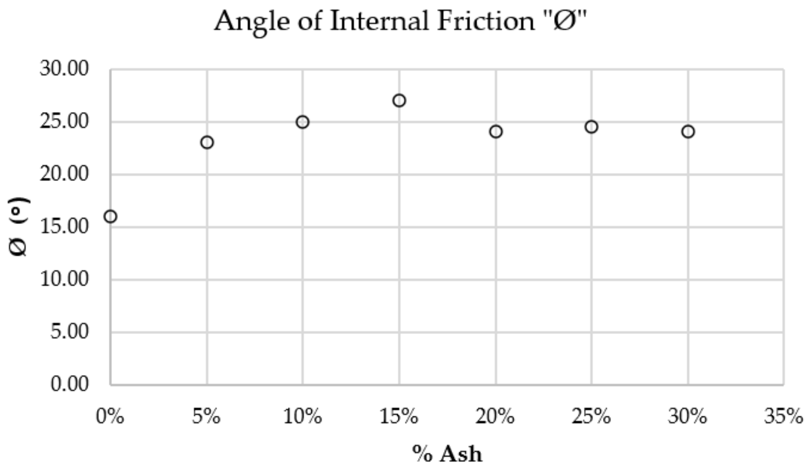

Figure 11. Internal Friction: soil + biosolids ash.

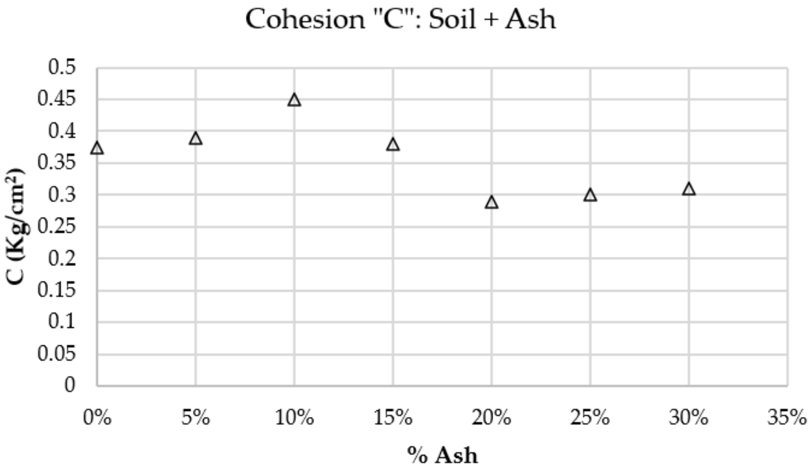

Figure 12. Cohesion: soil + biosolids ash.

Both graphs show that both the angle of internal friction and the cohesion of the soil increase significantly when 10 to 15% ash is incorporated into the clays. Compared to the natural soil, internal friction increases by approximately 60%, while cohesion increases by around 80%.

3.2.5. One-Dimensional Consolidation: Compressibility Index

The consolidation test performed on the soil and its various mixtures allowed for the evaluation of the material's compressibility. Figure 13 shows the variation in the compressibility index for each combination evaluated.

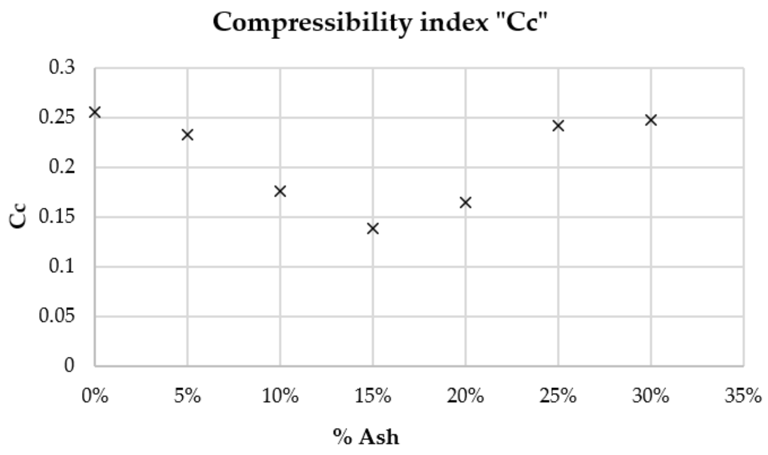

Figure 13. Compressibility index: soil + biosolids ash.

The behavior shown in Figure 12 indicates that the lowest compressibility is achieved by incorporating 15% ash into the soil, which represents an improvement of up to 45%.

3.2.6. California Bearing Ratio (CBR) Test: Expansion and Deformation

The CBR test allowed for the evaluation of soil expansion and resistance to deformation, both in its natural state and in mixtures with ash. Figures 14 and 15 illustrate the behavior of these properties, while Table 3 details the expansion values of the samples. In this table, the sample columns correspond to the different compaction energy levels: No. 1 (12 blows), No. 2 (26 blows), and No. 3 (56 blows).

The results presented in Figure 14 indicate that soil expansion decreases when incorporating between 10 and 15% biosolids ash, while it increases in mixtures with higher proportions. Furthermore, the CBR values shown in Figure 15 demonstrate a significant increase for all ash percentages evaluated, for both 0.1" and 0.2" strains.

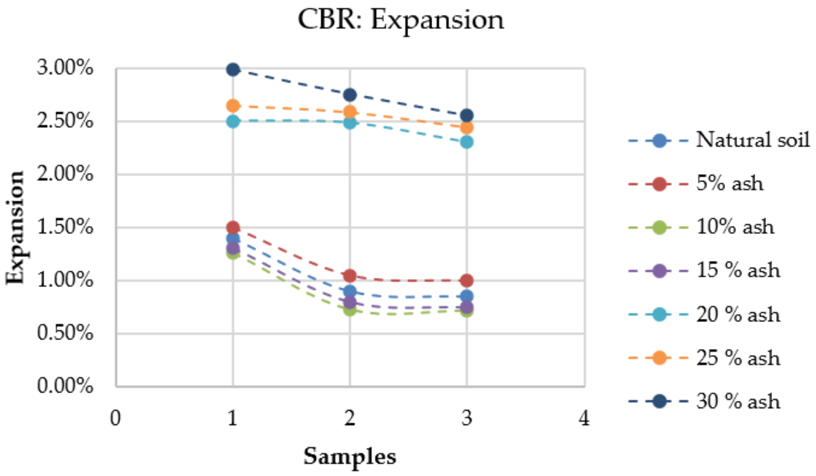

Figure 14. CBR Expansion: soil + biosolids ash.

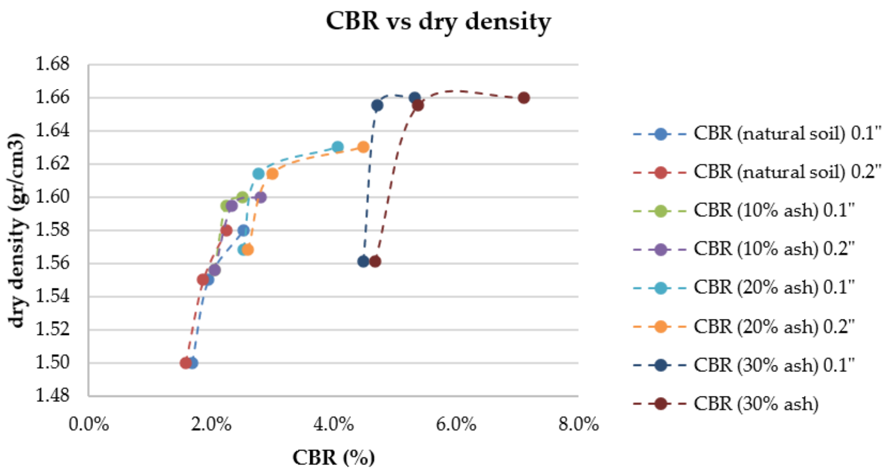

Figure 15. CBR Vs. dry density: soil + biosolids ash.

Table 3. CBR: Soil expansion + biosolids ash.

Samples (number of blows)	Expansion (natural soil)	Expansion (5% Ash)	Expansion (10% Ash)	Expansion (15% Ash)	Expansion (20% Ash)	Expansion (25% Ash)	Expansion (30% Ash)
1	1.40%	1.500%	1.261%	1.30%	2.50%	2.65%	2.98%
2	0.90%	1.050%	0.730%	0.80%	2.48%	2.58%	2.75%
3	0.85%	1.000%	0.720%	0.75%	2.30%	2.44%	2.55%

4. Discussion

Incineration of dried sludge at 900 °C yielded biosolids ash used to stabilize clays in proportions of 5 to 30%. Although the specific gravity of the mixtures decreased, the geotechnical properties of the soil improved, in accordance with that reported by Kadhim et al. [60] and Demir & Cabalar [63].

Soil plasticity, assessed by the liquid and plastic limits, decreases markedly with the incorporation of ashes, with reductions consistent with those reported by Kadhim et al. [60], Demir & Cabalar [63], and Al-Sharif & Atton [54], who documented decreases in the liquid limit of up to 40%. In contrast to the results of Kadhim et al. [60], the modified Proctor T-180 test shows an increase in maximum dry density for mixtures containing between 10 and 15% biosolids ash.

CBR tests show a significant increase in soil strength, accompanied by a reduction in its expansion, for ash contents between 10 and 15%. These results are consistent with the findings of Kadhim et al. [60] and Maghoolpilehrood et al. [58], who report substantial improvements in CBR values through the incorporation of biosolids ash as a stabilizing agent.

Soil compressibility is significantly reduced with the incorporation of ash, in accordance with the results of Maghoolpilehrood et al. [58] and Disfani et al. [59], who reported decreases in both the consolidation coefficient and compressibility parameters when using biosolids-derived additives, especially at concentrations close to 10%.

Regarding shear strength, direct shear tests show significant increases in both the angle of internal friction and soil cohesion. Although Maghoolpilehrood et al. [58] used triaxial tests, their results are consistent, showing substantial improvements in shear strength after the incorporation of ash. Similarly, Zabielska [62] indicates that sludge ash, used as an additive or replacement material in soil, improves various geotechnical properties—including the CBR—which coincides with the results obtained in the present investigation.

esidual sludge exhibits properties that, in its natural state, are unfavorable for the mechanical improvement of soils. However, its stabilization, treatment, and transformation can be beneficial, enhancing the soil's mechanical properties. This approach aligns with the criteria proposed by Zhang and Han. [64,65]

5. Conclusions

The results of this research allow us to draw the following main conclusions:

1. The geotechnical tests carried out confirm that sewage sludge ash can be used as an additive to improve the physical and mechanical properties of medium-plastic clay soils.

2. The ash obtained by incinerating dry sludge was mixed with the soil in proportions of 5, 10, 15, 20, 25, and 30% by weight, resulting in a reduction of up to 55% in the sludge mass and a maximum specific gravity of 2.52 g/cm³ at 900 °C, dependent on the incineration temperature.

3. The specific gravity of the mixtures is lower than that of the natural soil; however, the maximum density is reached with 15% ash, a proportion that also reduces the soil's plasticity by approximately 10%.

4. The maximum dry density, evaluated using the modified Proctor T-180 test, is obtained in mixtures with 10–15% ash.

5. The soil's mechanical strength improves significantly with the incorporation of 15% ash: the angle of internal friction increases by 60% and cohesion by 80% compared to the natural soil.

6. Soil compressibility decreases by up to 45% with the 15% ash mixture, while bearing capacity, evaluated by using the CBR, shows significant increases and a reduction in expansion of approximately 20%.

7. Overall, the results show that a 15% ash content from residual sludge optimizes the soil's geotechnical properties, improving its physical and mechanical behavior.

8. Research shows that the reuse of residual sludge is an effective strategy for soil improvement in civil works, also offering an environmental benefit by valorizing waste from treatment plants.

9. This research demonstrates that the reuse of residual sludge represents a sustainable, environmentally friendly and ecologically responsible strategy for the geotechnical improvement of soil, providing engineering benefits for civil works and a significant solution for the valorization of wastewater treatment plants.

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Abbreviations

The following abbreviations are used in this manuscript:

BA	Biosolid Ashes
CBR	California Bearing Ratio
SSA	Sewage Sludge Ash
LD	Linear dichroism
SS	Sewage Sludge

WWTP	Wastewater treatment plants
EPA	Environmental Protection Agency
VOC	Volatile Organic Compounds

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