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Eco-Friendly Cement Mortar with Wastewater Treatment Plant Sludge Upcycling

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Abstract: This study aimed to investigate the technical feasibility of replacing cement in mortar production with sludge generated in wastewater treatment plants (WWTPs), prepared using different treatments. The sludge used in the experiments was processed using four different methods to investigate the effect of processing on the mechanical strength of the specimens. The sludge was then mixed with mortar in different proportions, and samples were produced for flexural and compressive strength tests. The results showed that specimens with 7% sludge from the burned treatment exhibited the highest resistance, surpassing the standard. Specimens with sludge from the drying treatments showed similar results. This study found that using sludge in mortar production could lead to energy savings compared to traditional cement production methods. Moreover, the incorporation of sludge resulted in mortars that met the specifications of the EN 998-1:2018 standard, thereby indicating their technical feasibility. Therefore, this study demonstrated the potential of using sludge from WWTPs as a substitute for cement in mortar production, which could contribute to the reduction in the environmental impacts caused by civil construction and the development of sustainable alternatives for the disposal of sludge generated in WWTPs.

Keywords: eco-friendly; mortar; sludge; mechanical resistance; energy consumption

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1. Introduction

Circular economy is a production strategy that aims to be sustainable, regenerative, and restorative by ensuring that all materials are efficiently extracted, circulated, and returned to production without a loss in quality [1]. This system enables end-of-life products to be transformed into resources for other production processes, closing cycles in industrial systems and reducing waste [1]. To prevent waste and maximize economic and environmental value, a circular economy strategy efficiently manages natural resources, minimizes or eliminates waste creation, and maximizes the life and value of products [1].

As water consumption increases, so does the amount of sludge generated in wastewater treatment plants (WWTPs) [2]. The sludge generated from the digester is classified as biomass and is a by-product of wastewater treatment plants (WWTPs). It falls under the waste category of L.E.R. code 19 08 05, specifically designated for sludges resulting from the treatment of urban wastewater. Generally, these sludges are not sanitized and are either collected, transported, temporarily stored, or directly utilized for composting purposes [3]. Alternatively, they may also be applied to agricultural soils or deposited in landfill [3]. In 2020, over 333,000 tons of sludge were processed by WWTPs in Portugal; in

2021, the number was 360,000 tons. Those numbers only relate to sewage sludge; in supply sludge, the numbers were 18,000 in 2020 and 22,000 tons in 2021 [4].

Due to the presence of residual organic pollutants, toxic metals, and pathogenic microorganisms in sewage sludge, proper treatment and disposal processes are necessary to protect public health and preserve the environment [5]. However, despite being classified as waste, sewage sludge can be used as a source of energy or resources, which presents an opportunity for waste management within the circular economy [5]. Techniques such as nutrient recovery (e.g., phosphorus and nitrogen), heavy metal recovery, sludge-based absorbents, protein and enzyme recovery, and the production of lightweight aggregates, bricks, interlocking tiles, coal, and slag can be used to sustainably produce sludge [5,6]. Additionally, sludge can be used as an energy source by producing biogas or as a biofuel [5].

The mineral composition of sludge is essentially hydroxides and oxides of silica, aluminum, and ferric [6]. This characteristic of sludge allows for its application as a construction material [6,7]. The valorization of the sludge to transform it into safe and stable products mitigates some of the expensive and energy-consuming stages for something that will be discarded [7].

Water is the most consumed material worldwide, followed by concrete, which is composed of cement, aggregate, and water [8]. Portland cement is a finely powdered material with excellent agglomerating properties. It can harden when mixed with water and maintain its stability even in the presence of water, which is why it is classified as a hydraulic binder. The production of Portland cement requires the extraction of limestone, clay, sand, and iron ore, making them essential components [9].

The cement production process is highly polluting, generating impacts in practically all production phases from extraction to disposal [10,11]. CO_2 emissions from the cement industry represent more than 5% of the global emissions and are estimated to reach 30% by 2050 [10].

The combination of cement and water produces cement paste, which forms a mortar when cement paste is mixed with sand [12]. Therefore, mortar is a homogeneous mixture of binder (cement, plaster, or lime), fine aggregates, and water. Concrete is formed by adding coarse aggregates, such as gravel or stone, to mortar [12].

The type of bonding agent used determines the classification of the mortar. When a single binder is used, it is referred to as simple mortar, whereas the combination of two binders, such as cement, plaster, and lime, creates a mixed mortar [12]. Specific characteristics or properties can be achieved by incorporating additives or admixtures into mortar to meet the desired specifications [12].

Mortar can be classified based on the nature of the binder, consistency, plasticity, density, and method of preparation or supply [12]. Additionally, mortars can be classified according to their intended functions, such as masonry construction, wall and ceiling cladding, floor cladding, ceramic cladding, and structural restoration [12].

Standards such as EN 998:1-2017 define the classification and quality evaluation requirements for mortars [13]. EN 13139:2005 specifies the properties of aggregates used in different types of mortar applications, whereas EN 197-1:2012 presents the technical requirements and compliance criteria for various types of cement available [14,15].

The use of waste in civil construction products is a promising approach for reducing the environmental impact of the cement industry [11]. This attitude not only minimizes waste disposal in landfills, but also reduces the volume of extracted materials, thus minimizing the industry's environmental impact [10]. By-products can be used to fill buildings and make concrete aggregates and sidewalks [10]. Replacing or complementing a cement binder in a concrete product is one of the most interesting applications [10].

Blast furnace slag is a by-product of the steelmaking industry [16]. During the cooling process, the slag forms a glassy product that can be crushed and added to cement mixtures to create slag cement. Incorporating slag into a mixture enhances its strength [16]. The use of slag cement in airport runways has demonstrated that a reduced thickness achieves the same effectiveness as concrete paste with Portland cement [16]. This reduction contributes to a decrease in greenhouse gas emissions associated with runway production [16].

The particles emitted during coal combustion, known as fly ash, can be captured using air pollution-control devices [10]. In 2012, the United States produced 52.1 million tons of fly ash, with 11.8 million tons utilized in the production of concrete, concrete products, and grout [6]. Replacing 10–20% of cement with fly ash in concrete paste enhances the compressive strength and corrosion resistance [17].

Because of its chemical composition similarity to clay, water station sludge presents an opportunity to replace clay in the manufacturing of bricks and ceramic materials (tiles and blocks) [10]. These materials facilitate the solidification and immobilization of potentially toxic elements found in the sludge [10]. However, bricks incorporating sludge exhibit reduced compression resistance and increased water absorption [10].

The incorporation of sludge in construction products affects the characteristics of manufactured items owing to the presence of organic substances and heavy metals [7]. When fine aggregates are partially replaced in concrete mixtures, sludge can deteriorate the properties of the concrete [7]. In ceramic materials, the addition of dry sludge introduces porosity and an uneven surface, affecting the water absorption and resistance to ice [7].

To enhance the strength, pozzolanic additives can be introduced into cement. The pozzolanic activity involves binding lime in the presence of water, resulting in the formation of water-insoluble calcium silicates [7]. Although the addition of sludge may affect mixture fluidity by absorbing water and prolonging the setting time, it contributes to an increased compressive strength [7].

Sustainable construction practices and waste management drive the incorporation of WWTP sludge into construction products, resulting in a practice that minimizes the impacts generated by the cement industry while providing a safe and stable destination for sludge [7,10,11].

The volatile compounds and organic matter in sludge can degrade or decompose, altering the manufactured product and reducing its durability [18]. Therefore, it is necessary to eliminate these compounds before using sludge as a construction ingredient [18]. The mineralogical alteration of the sludge is advantageous because it can enhance the pozzolanic activity of the final product through material rearrangement [19].

Thermal processes have the advantage of reducing the volume and weight and recovering energy through steam turbines [20]. For instance, incineration involves the complete oxidation of volatile matter, producing an inert residue known as ash [20,21]. In the European Union, approximately 22% of sewage sludge is incinerated [22]. Another alternative is to incorporate ash into building materials, resulting in stable and safe products [20,21].

After incineration, approximately 30% of the solid waste weight was converted into ash, which accounted for only 10% of the initial volume. These ashes typically contain high levels of heavy metals, posing a challenge for their proper disposal. However, incorporating ash into construction materials offers a viable solution, resulting in stable and safe products [20,21].

The burning of sludge as an alternative fuel and subsequent incorporation of the resulting ash into the final product proved to be a more favorable approach than independent incineration methods [21].

The present study aimed to produce and evaluate, from a technical and economic perspective, the ecological mortar produced from the replacement of cement by sludge from WWTPs, prepared by different treatments. The sludge was characterized and subjected to various thermal treatments before being incorporated into the mortar. The technical feasibility of the treatments was discussed based on the mechanical resistance of the produced specimens. The economic feasibility was evaluated based on the energy expenditure of the sludge treatment processes compared to the energy expenditure of cement production.

2. Materials and Methods

The sludge used in the experiments was obtained from a WWTP (sewage treatment) located in Bragança, a city in northeastern Portugal. The sludge had a pH of 7.8, moisture content of 83.2% ± 0.2%, total solids of 16.8% ± 0.2%, ash content of 20.1% ± 0.2%, and organic matter of 20.7% ± 4.4%.

2.1. Analytical Methods

Sludge pH was determined using the soil methodology described by Embrapa (1997) [23]. Sludge (100 mL) was dissolved in 100 mL of distilled water and magnetically stirred for 15 min. After allowing it to rest for 10 min, the pH of the supernatant liquid near the phase-change interface was measured using a calibrated pH meter.

Moisture and total solids were determined simultaneously using the methodology presented in Section 2540—SOLIDS [24]. In a porcelain crucible that was pre-dried in an oven at 105 °C for 24 h, 3 g of sludge was dried at 105 °C for 2 h. The mass of the crucible containing the sludge was measured at regular intervals of 1 h until a constant weight of the dry sludge sample was achieved (with a variation of 4% or 50 mg, whichever occurred first). The calculation of humidity involved determining the difference between the weight of the wet material and the weight of the dry material, divided by 100. Total solids, on the other hand, were obtained by taking the ratio of the weight of the dry material to the weight of the sample at the beginning, multiplied by 100.

To quantify the organic matter content, 250 mg of dry and finely ground sludge was processed according to the methodology suggested in [25]. The dry and ground sludge (250 mg) was combined with 10 mL of 1N potassium dichromate solution and 20 mL concentrated sulfuric acid. The mixture was stirred for 1 min with gentle rotation and left undisturbed for 30 min. Following this, 200 mL of distilled water, 10 mL of concentrated orthophosphoric acid, and 1% ferroin indicator were added. The resulting mixture was titrated with a 0.5 N ammonium ferrous sulfate solution until a green color was achieved. For the blank, the same procedure was repeated without the sludge addition. Organic matter content was calculated using Equation (1).

$$OM = 1.725 \times [10 - (V_2 \times 10 \times V_1{}^{-1})] \times 0.4/m, \tag{1}$$

where OM represents the organic matter in %, V_1 is the volume of ammoniacal ferrous sulphate spent on blank titration (mL), V_2 is the volume of ferrous ammonia sulphate spent on the titration of the sludge sample (mL), and m is the mass of the sludge sample analyzed (g).

2.2. Sludge Preparation

Various techniques have been employed to prepare sludge before introducing it into mortar blends as a partial cement substitute. The suggested methods were investigated based on the mechanical strengths of the resulting specimens.

2.2.1. Method 1: Dry Sludge

The production of specimens using solely dry sludge was used as a standard for other analyses, as the sludge underwent only water removal and did not undergo any additional physical or chemical alterations. The material was dried by spreading into a thin layer inside a porcelain crucible. This method increases the contact surface area with heat from the oven, thereby enhancing the efficiency of the drying process. The sludge was dried for 24 h at 105 °C (referred to as M1) [18,26,27].

2.2.2. Method 2 and 3: Dry Sludge in the Sun

A sample of sludge was dried naturally in the sun for 7 (M2) and 15 (M3) days, in contrast to the method used in [28], where the sludge was left to dry for a month. The sludge was spread in a thin layer in an aluminum container, exposed to the sun daily, and covered at night to prevent the accumulation of moisture. The residual moisture content was determined.

2.2.3. Method 4: Incineration

The dried sludge (105 °C for 24 h) was combusted at 300 °C for 0.5 h and 900 °C for 3 h inside a muffle furnace (M4) to ensure the complete decomposition of organic matter and facilitate mineralogical changes for increased pozzolanic activity [7,18,26,29,30].

2.3. Mortar Specimens

The mould used to prepare the specimens was prismatic. Each piece weighed approximately 600 g, and two specimens were made per sludge concentration used. One sample was used for the tests on the 7-day curing age, and the other for the 28-day curing age. The specimens were created using tap water, 0.4 mm sand, and limestone Portland cement (Cimpor CEM II/B-L 32.5N). The sand was dried at 105 °C for 24 h before being used in a mortar. All specimens were prepared using the same proportions of sand and water, with concentrations of 54% and 14%, respectively. The cement was replaced by sludge treated using the methods mentioned above, at levels of 0%, 3%, 5%, 7%, and 10%. The 0% replacement refers to the standard manufactured for each production batch of test specimens. This was performed to investigate the impact of cement replacement on the final mechanical strength. Therefore, each batch comprised two standard specimens, meaning that they did not involve the incorporation of sludge, along with two specimens for each concentration of replacement of cement by sludge. This approach allowed for carrying out a batch of tests per slurry preparation process.

The preparation, production, and storage of the specimens were performed in accordance with NBR 5738 [31]. In a stainless-steel tank attached to a mechanical mixer, water, cement, and treated sludge, when required, were first added and mixed at low agitation (140 rpm around the shaft) for 30 s. Without pausing the agitation, sand was then introduced, and the agitation speed was increased to high speed (285 rpm around the shaft) for an additional 30 s. Following this period, the materials present on the wall of the tank were transferred to the mixture using a spatula, and the mixture was stirred for 1 min at high speed.

A mineral oil was used to lubricate the inner surfaces of the molds. The paste was applied to the molds by using a horizontal compactor with 70 strokes per layer. Once the specimens were produced, they were placed under a bench in a geotechnical laboratory for 48 h. After this period, they were removed from the molds and transferred to a humid chamber, where they were kept at a temperature of 20–25 °C with 90% humidity for 7-day and 28-day age curing.

2.4. Mechanical Tests

Two mechanical tests, flexural strength and compressive strength tests, were conducted on the mortars after 7-day and 28-day age curing. In the flexural test, a force was applied to the center of the specimen horizontally until it ruptured, whereas in the compression test, a force was applied 4 cm from the end of the specimen until the peak force was reached [13]. Statistical analysis of the compressed data was performed using Tukey's honestly significant difference (HSD) procedure with a 95% confidence level, after performing one-way analysis of variance (simple ANOVA) on the data. Statistical analyses were conducted using the STATGRAPHICS Centurion software.

Mortar is classified by the compressive resistance that the specimen can withstand after 28 d of curing, according to EN 998-1 standards [13]. The mortar is classified into four categories, CS I, CS II, CS III, and CS IV, based on their compressive strength ranges, which are 0.4–2.5 MPa, 1.5–5.0 MPa, 3.5–7.5 MPa, and more than 6 MPa, respectively [32].

2.5. Economic Viability

The cost-effectiveness of each sludge preparation method was assessed based on the energy required for each method and the potential energy savings resulting from replacing the cement with sludge in the mortar. The savings or replacement costs were calculated using Equation (2):

$$A = B - (B \times c) + (D \times e), \tag{2}$$

where A represents the economy or cost of kWh t^{-1} cement, B is the energy expenditure required to produce one ton of cement in kWh t^{-1} cement, c is the fraction of cement concentration, D is the energy expenditure required to treat one ton of sludge in kWh t^{-1} sludge, and e is the fraction of sludge concentration.

The energy costs for both sludge treatment and cement production were obtained from previous studies conducted by other researchers. Table 1 provides the values of these costs.

Table 1. Energy demand for preparation of sludge.

Process	Electricity Demand
Cement production	102 kWh t^{-1} cement [33]
Drum or fluidized bed dryers	0.07 kWh $kg^{-1}{}_{H2O}$ [34]
Drying operation	39 kWh t^{-1} dry sludge [35]
Dry sludge and incineration	275 kWh t^{-1} dry sludge
	−1024.5 kWh t^{-1} dry sludge (recovery) [35]
Co-incineration	−250 kWh t^{-1} of dry sludge (recovery) [36]

3. Results

3.1. Sludge Preparation

Assuming that all water was eliminated in the M1 preparation methodology, the moisture content of M1 was 0%. The sludge in this methodology can be observed in Figure 1a. In addition to other factors, the ambient temperature affects the solar-drying process of the sludge. During the drying period, the average temperature for M2 was 14.1 °C, with an average maximum of 18.2 °C and an average minimum of 11.5 °C. For M3, it was 21.3 °C, with an average maximum of 23.6 °C and an average minimum of 19.8 °C. Figure 1b,c show the drying system employed for the sludge. The residual moisture content of the sludge after drying was 5.5% for M2 and 4.0% for M3. The sludge before and after burning are shown in Figure 1d,e, respectively. In summary, Figure 1a M1—sludge after the drying process; Figure 1b—sludge during the sun-drying process; Figure 1c M2/M3—sludge after the sun-drying process; Figure 1d—sludge before the burning process; and Figure 1e M4—sludge after the burning process.

3.2. Mechanical Tests

The tests aimed to detect the effects of incorporating treated sludge particles into concrete mortar.

Figure 2 displays the final flexural strength of each specimen for each method, whereas Figure 3 illustrates the final compressive strength obtained for each specimen, along with the standard deviation (vertical line). A simple ANOVA was conducted with each mortar preparation method and concentration considered as distinct treatments, resulting in the analysis of 38 observation points at 19 levels. The lowercase letters in Figure 3 represent homogeneous groups created according to the Tukey's test.

The results indicated that only the specimen with 7% M4 demonstrated a greater mechanical resistance than the standard. The dry sludge specimens exhibited similar values and behaviors in terms of the resistance drop profile and resistance values.

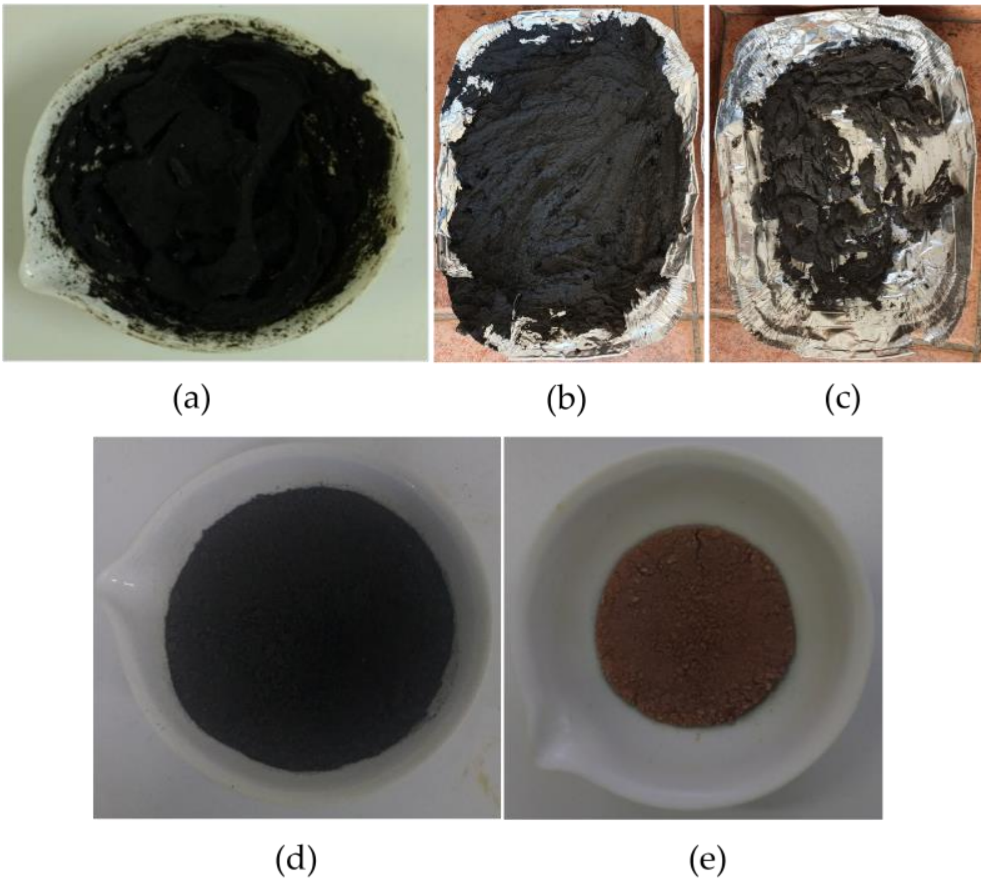

Figure 1. Sludge preparation for the different methodologies employed (**a**–**e**).

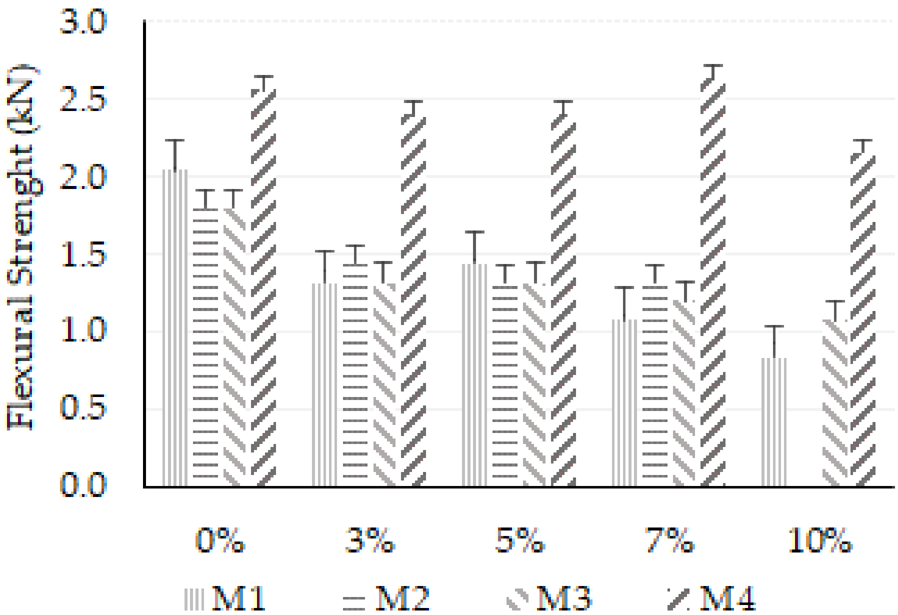

Figure 2. Flexural strength at 28-day age of curing acquired using a mortar for each treatment and substitution concentration (M1: 105 °C 24 h; M2: sun 7 d; M3: sun 15 d; M4: 300 °C 0.5 h + 900 °C 3 h).

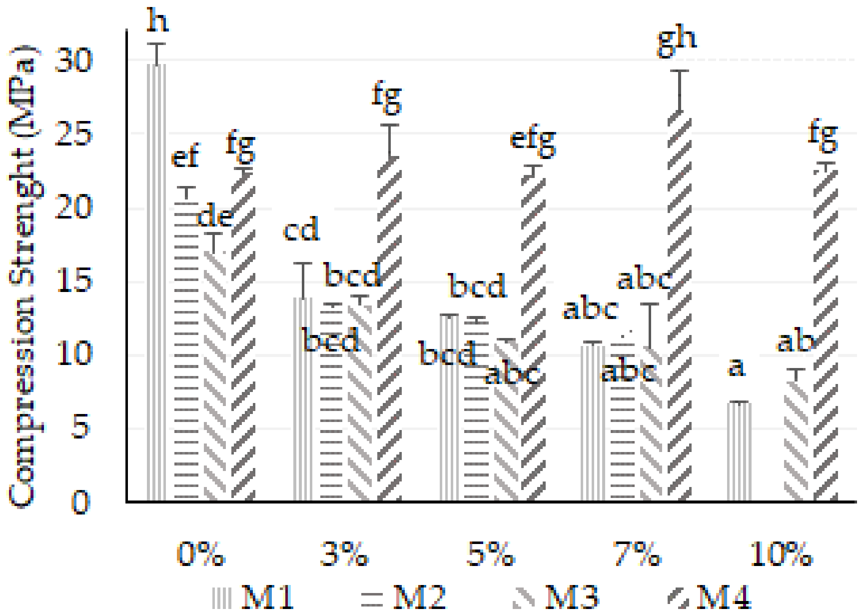

Figure 3. Compressive strength at 28-day age of curing acquired by the mortar for each treatment and substitution concentration and division of the mortars produced into homogeneous groups—lowercase letters (Tukey multi-comparison test, $p \leq 0.05$) (M1: 105 °C 24 h; M2: sun 7 d; M3: sun 15 d; M4: 300 °C 0.5 h + 900 °C 3 h).

4. Discussion

Fonseca (2018) performed experiments using dry sludge as a replacement for cement in mortar specimens, but the results were different [37]. At a concentration of 5%, there was an improvement in both the flexural and compressive strengths compared to the standard [37]. However, the specimen with a 10% concentration showed a similar flexural strength but a 27% lower compressive strength than the standard [37].

Ingunza et al. (2018) found that incorporating sludge ash into mortar resulted in a higher mechanical resistance for both the flexural and compressive strengths compared to standard mortar [38]. The authors tested different concentrations of sludge ash ranging from 0% to 20% by replacing a portion of the cement mass [38].

While increasing the concentration of sludge particles decreased the flexural strength of the specimens, the optimal concentration for dry sludge (M3 and M1) was 5%, which was also reported as the optimal concentration for the flexural strength in Fonseca's (2018) study [37]. In contrast, for M4, the ideal concentration is 7%. In the study by Ingunza et al. (2018), the highest flexural strength was achieved with 20% ash, but it remains unclear whether this concentration represents the optimal maximum, as the researchers did not test higher concentrations [38].

The differences in standards observed for each methodology might be attributed to variations in the cement caused by the way the bags were stored after being opened, as well as inconsistencies in the quality of the sand used.

The researchers performed two additional statistical analyses on the compressive strength data. In one of the analyses, the sludge concentration was not considered, and the data were only analyzed based on the mechanical resistance obtained depending on the sludge treatment. In another scenario, the analysis was performed without considering the preparation method, and the data were analyzed based on both the mechanical strength and sludge concentration in the mortar. The groups of samples (called as a, b and ab) that were statistically similar according to the Tukey's test are presented in Table 2.

Table 2. Homogeneous groups identified by Tukey multi-comparison test ($p \leq 0.05$) within which there are no statistically significant differences.

Treatment	Average (MPa)	Concentration (%)	Average (Mpa)
M3	10.81 a	10	12.52 a
M1	11.00 a	5	14.50 ab
M2	12.26 a	7	14.80 ab
M4	23.70 b	3	16.02 ab
		0	22.45 b

a, b and ab; homogeneous groups of Tukey's test.

The techniques used for drying (M1–M3) belong to the same category (a) and therefore share similarities. On the other hand, M4 stands out because it yields the highest average resistance in a different category. When examining the impact of cement replacement with treated sludge in the fourth column of Table 2, it was discovered that concentrations ranging from 3 to 10% are comparable (all belong to category (a)). Nonetheless, only the 10% replacement differed significantly from the standard (0%).

4.1. Dry Sludge (M1–M2)

The study found that drying sludge in the sun did not result in significant chemical changes in the material. The only difference observed was the moisture content of the particles, which depended on the sludge formulation. Overall, if the drying process is efficient and favorable weather conditions exist, the quality of the mortar made from sun-dried sludge particles is similar to that of oven-dried sludge particles.

All the mortars containing dry sludge particles exhibited a compressive strength greater than 6 MPa, placing them in the CS IV [32] category. These mortars are suitable for use in general-purpose rendering/plastering, colored rendering, and one-coat rendering for external applications. However, it is important to determine other parameters, such as dry bulk density, adhesion, and capillary water adsorption, for these applications.

4.2. Sludge Ash (M4)

The study found that all mortars produced using M4 particles were classified as CS IV [32], and the hardening of cement was due to a chemical hydration reaction rather than drying. Various factors, such as the clinker quality, water/cement ratio, aggregate quality and content, and calcium hydroxide dosage, affect the mechanical strength of mortars [39]. Burning sludge at 900 °C enhances its pozzolanic activity, which involves binding lime in the presence of water to form insoluble calcium silicates [22]. The addition of sludge may decrease the fluidity of the mixture but can still contribute to improving the compressive strength of the mass [7]. Studies have shown that there is an optimal percentage of sludge ash incorporation for peak compressive strength, with a 7% cement replacement with sludge ash being the ideal concentration for achieving peak mechanical resistance [29].

4.3. Economic Viability

The average global demand for electric energy for the cement industry was 102 kWh t^{-1} cement in 2017, with a range of 90 to 150 kWh t^{-1} cement, depending on the efficiency and type of production process [33,40]. Additionally, the thermal energy demand for cement production is approximately 3.38 GJ t^{-1} clinker [40]. In the calculations of the economic viability of mortar production under the conditions studied, two endpoints of 3% and 10% were considered.

Schnell et al. (2020) conducted a literature review and found that drum or fluidized bed dryers that transfer heat to the sludge by conduction and convection, which can be by hot gas or steam, consume about 0.07 kWh kg^{-1}_{H2O} [34]. To evaporate 777 kg H_2O (dry from 83.2% to 5.5% humidity) per ton of dry sludge, the electric energy demand is 54.4 kWh t^{-1} dry sludge. For the cement portion of the mortar, the electricity consumption is 100.6 kWh t^{-1} cement for 3% concentration and 97.2 kWh t^{-1} cement for 10%.

Xu et al. (2014) collected data indicating that the drying operation requires 39 kWh t^{-1} dry sludge and 1.53 kWh t^{-1} dry sludge, whereas incineration demands 275 kWh t^{-1} dry sludge but allows for an energy recovery of 1024.5 kWh t^{-1} dry sludge [35]. Using this information, the consumption of electricity in the drying process for incorporating sludge into mortar was calculated to be 100.1 kWh t^{-1} cement for 3% and 95.7 kWh t^{-1} cement for 10%. The electrical consumption for the incineration process was determined to be 76.5 kWh t^{-1} cement for 3% and 16.9 kWh t^{-1} cement for 10% of the cement fraction in mortars with sludge ashes.

In another study by Lundin et al. (2004), the co-incineration of WWTP sludge and waste generated 2300 kWh t^{-1} of district heating and 250 kWh t^{-1} dry sludge of electricity through combined heat and energy production [36]. In this case, the electrical consumption for incorporating sludge into mortar was calculated to be 91.4 kWh t^{-1} cement for 3% and 66.8 kWh t^{-1} cement for 10%. The use of ash in this scenario represents savings of 10.6 kWh t^{-1} cement for 3% and 35.2 kWh t^{-1} cement for 10%. Table 3 presents the energy savings calculated for each process.

Table 3. Energy savings according to the reference values.

		Energy Saving (kWh t^{-1} Cement)	
Process	**Electricity Demand**	**3%**	**10%**
Drum or fluidized bed dryers	0.07 kWh $kg^{-1}{}_{H2O}$ [34]	2.6	8.6
Drying operation	39 kWh t^{-1} dry sludge [35]	1.9	6.3
Sun-drying	0	3.1	10.2
Dry sludge and incineration	−749.5 kWh t^{-1} dry sludge [35]	25.5	85.2
Co-incineration	−250 kWh t^{-1} dry sludge [36]	10.6	35.2

5. Conclusions

This study investigated the feasibility of using WWTP sludge in mortars as a construction material. The mechanical properties and economic viability were evaluated by comparing the energy production costs of the cement production and sludge preparation. The results suggest that the sludge can be used in small amounts without affecting the mechanical strength of the mortar and that the quality of the mortar may improve when 7% of cement is replaced with ash. Sludge preparation via incineration or drying can contribute to energy savings. Incorporating up to 10% sludge into the mortar maintained the same level of strength as the standard version. This study concludes that the use of WWTP sludge in mortar is a sustainable and environmentally friendly option for civil construction.

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