



Toward Greener Mortars with Wastewater Sludge as Cement Replacement

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Abstract

The cement industry significantly impacts environmental issues, leading to growing demand and research into developing alternatives that result in more environmentally friendly building materials. This research investigates the potential of using sludge from the Bragança Wastewater Treatment Plant (WWTP) as a partial substitute for cement in the formulation of mortar, offering a more eco-friendly solution while promoting waste reutilization. The sludge was prepared using five different methods to evaluate this possibility. M1 was oven-dried, M2 and M3 were sun-dried, M4 was incinerated in a muffle furnace, and M5 was pyrolyzed. Compression tests were carried out to evaluate the mechanical strength of the mortar. Different mixtures were formulated and analyzed, and the M3 specimen containing 7% sludge, showed the highest strength, outperforming the control mortar and those with M1, M2, and M4 sludge preparations, which displayed similar results. On the other hand, the mixture subjected to the pyrolysis treatment (M5) showed the least satisfactory results in terms of strength, even lower than those obtained for the control mortar. Considering the environmental perspective and the pressing need to move towards a circular economy, evaluating the associated energy consumption and mechanical performance is essential. The findings indicated that partial substitution of cement with treated sludge led to a noticeable decrease in energy demand, particularly when low-energy processes like solar drying were employed. It is important to highlight that all the modified mortars, following different methods, were shown to comply with the EN 998-1:2018 standard for compressive strength, which attests to their viability for practical applications. The incorporation of WWTP sludge in mortar production not only reduces cement consumption but also minimises the environmental impacts associated with this industry. At the same time, it contributes to sustainable waste management and economic valorization. The study highlights the feasibility of using mortars incorporating sludge as a cost-effective alternative that also plays a role in mitigating environmental issues. Further studies should assess long-term durability and potential environmental trade-offs, in order to clarify the practical impact of this strategy in actual construction scenarios.

Keywords: circular economy, economic valorisation, mechanical strength, sludge ash, sludge sun dry

1. Introduction

The circular economy is a forward-thinking model that redefines how resources are managed in production systems. Unlike traditional linear approaches, it emphasizes sustainability by keeping materials in use for as long as possible. Products and materials are carefully designed from the outset to be recovered, refurbished, or recycled, maintaining their integrity through multiple life cycles. When items reach the end of their initial purpose, they are not discarded but instead serve as valuable inputs for new manufacturing processes. This systemic shift minimizes waste, optimizes resource use, and fosters a more resilient industrial ecosystem [1].

To avoid waste and loss of economic and environmental value, the circular economy strategy suppresses inefficiencies in the production process by efficiently managing natural resources, reducing or eliminating waste generation, while extending the lifespan and value of products [1].

Over the years, water consumption has presented a growing trend, and in alignment with this trend, the amount of sludge generated in WWTPs has increased [2]. In 2020 in Portugal, the treatment facility handled more than 333,000 tons of residual sludge from wastewater treatment plants [3]. Due to the significant concentration of persistent organic contaminants, heavy metals, and harmful microbes found in wastewater sludge, adequate treatment and disposal processes are essential for the protection of public health and preservation of the environment [4]. While typically categorized as waste, sewage sludge contains valuable components suitable for energy production and material reclamation, representing the possibility of waste management within the concept of a circular economy [4]. Techniques exist to recover nutrients such as phosphorus and nitrogen, heavy metals, sludge-based absorbents, proteins, and enzymes from sewage sludge [4]. One way to manage the volume of sludge produced sustainably is to combine the mineralogical composition of the sludge, mainly consisting of silica hydroxides and oxides, aluminium and ferric with the production/application in construction materials [5]. The construction industry can utilise processed sludge as raw material for various products, including low-density aggregates, brick formulations, modular paving units, and additives for fuel and metallurgical byproducts. [4]. Sludge can be used as an energy source for the production of biogas or as a biofuel [4].

It is necessary to eliminate volatile compounds and degrade organic matter in sludge before incorporating them into construction materials [6]. This is because organic matter can degrade or decompose, causing changes in the manufactured product and thus reducing its durability [6].

Thermal processes have the advantages of reducing volume and weight, destroying toxic organic compounds, including pathogens, minimizing odors, and generating energy via steam turbines [7]. Thermal processing enables complete oxidation of organic matter, converting it into a chemically stable mineral ash residue [7,8]. Within EU member states, nearly one-quarter (22%) of treated wastewater sludge undergoes this high-temperature disposal method [9]. The resulting ash has a high heavy metal content; therefore, correct final

disposal can become a problem [7,8]. The incorporation of ash into construction materials results in stable and safe products [7,8].

Wet oxidation is a hydrothermal treatment (thermal hydrolysis) in which there is rapid solubilization of organic residues and liquid oxidation of dissolved organics or oxidizable inorganic compounds [10]. Typical operating conditions for wet oxidation are temperatures ranging from 150 to 330 °C and pressures ranging from 1 to 22 MPa using pure or atmospheric oxygen for 15 to 120 min [8], [10], [11]. In wet oxidation, low-impact exhaust gases are produced, and mineralized solid and high-resistance liquid fractions are produced [10]. The incorporation of mineralized solid fractions into construction materials is an alternative for the disposal of this fraction, which should be studied.

The construction industry currently depends on cement as its principal binding material, with concrete consumption volumes surpassing all other engineered materials combined [12]. There are impacts generated in practically all productive phases of cement, such as extraction, production, and final disposal [13], [14]. The cement industry contributes more than 5% of global CO₂ emissions, with projections indicating this could increase to 30% by 2050 [13].

The construction industry seeks solutions to minimize the environmental burden of concrete and mortar, so the incorporation of residues in these civil construction products should be encouraged [14]. The incorporation of waste in civil construction is an alternative for reducing the volume of waste deposited in landfills and the volume of mined materials, thus minimizing the environmental impact of the construction industry on the environment [13]. There are potential end uses of by-products such as building fillings, concrete aggregates, and pavements [13]. Environmentally conscious concrete production increasingly focuses on binder modification, where cement is either partially replaced or augmented with eco-friendly supplementary materials [13].

Aligning sustainable construction practices with waste management implements WWTP sludge in construction products as an alternative to minimize the impacts generated by the cement industry while simultaneously providing a safe and stable sludge destination [13], [15]. Thus, this study aims to produce and evaluate the technical feasibility and economic valorization of ecological mortar produced from the replacement of cement by WWTP sludge. The sludge was characterized and subjected to different thermal treatments before being incorporated into the mortar. The study assesses the viability of the treatment based on two main criteria: (1) structural performance, evaluated through compressive strength tests on the specimens, and (2) cost-effectiveness, determined by comparing the energy consumption of sludge processing with that of traditional cement production.

2. Materials and Methods

Sludge samples were sourced from a local wastewater treatment plant in Bragança, Portugal, Águas de Trás-os-Montes, and Alto Douro, part of the Águas do Norte Group.

2.1 Sludge Characterisation

The incorporation of sludge in mortar can affect the durability of the manufactured product because of the presence of organic substances; therefore, sludge characterization under analysis is essential [15]. The sludge was characterized considering organic matter (OM), total solids (TS), moisture content, and pH.

The pH measurement followed the standardized soil analysis protocol established by Embrapa [16], and moisture content and total solids were quantified using the gravimetric procedures outlined in Standard Methods for Water and Wastewater Analysis [17]. To quantify the organic matter (OM) content, around 250 mg of dried and ground sludge was combined with 10 mL of 1 N potassium dichromate and 20 mL of concentrated sulfuric acid, followed by gentle stirring. The mixture was then left to stand for 30 minutes [18]. Subsequently, 200 mL of distilled water, 10 mL of concentrated orthophosphoric acid, and a 1% ferroin indicator were added. This solution was titrated with 0.5 N ferrous ammonium sulfate until a green endpoint was reached [18]. A blank sample, prepared following the same steps but without sludge, was also used for comparison [18]. The OM content was calculated using Equation 1:

$$OM = 1.725 \left(10 - (V_2 - 10 V_1^{-1}) \right) 0.4/m \quad (1)$$

where

OM organic matter content (%)

*V*₁ volume of ammoniacal ferrous sulphate for blank (mL)

*V*₂ volume of ferrous ammonia sulphate for sludge sample titration (mL)

m sludge sample mass (g)

2.2 Sludge Preparation

Processed sludge was used to produce specimens with partial cement replacement. Various approaches have been suggested to evaluate how sludge processing affects the mechanical strength of the specimens.

Method 1: Dry Sludge

The preparation of specimens with only dry sludge served as a standard for the other analyses because the sludge had only water removal without other physical or chemical changes.

The sludge drying conditions (105 °C, 24 h) were selected in accordance with studies from Gonçalves et al. [6], Nakic [19], and Silva [20].

Method 2 and 3: Dry Sludge in the Sun

Adopting the natural drying method from Awere et al. [21], sludge samples were sun-dried under open atmospheric conditions; however, for periods of 7 and 15 days, the authors left them for a month. To increase the drying efficiency, a thin layer of sludge was used in an aluminium container, which was exposed to the sun every day during the experimental period and covered at night to avoid dew or rain. Following natural sun exposure, residual water content was determined by standard gravimetric methods using 105 °C oven drying for over 24 hours.

Method 4: Incineration

Following dehydration at 105°C for 24 hours, samples were subjected to stepwise thermal decomposition in a muffle furnace - first at 300°C for 0.5 hours, then at 900°C for 3 hours. The residence times and temperatures were defined based on the work of Gonçalves, Esteves, Carvalho, Machado, and Correia [6], Nakic [19], Hagemann, Gastaldini, Cocco, Jahn, and Terra [22], and Melo, Silva, and Oliveira Dias [23]. Burning the sludge at these temperatures and combustion times ensures complete decomposition of the sludge organic matter [19]. Furthermore, mineralogical alterations enable the rearrangement of matter, which increases the pozzolanic activity of the material [15].

Method 5: Wet Oxidation

The typical conditions for wet oxidation are temperatures between 150 and 330 °C and pressures from 1 to 22 MPa using pure or atmospheric oxygen, with residence times ranging from 15 to 120 min [8,10,11]. Due to technical constraints preventing testing under the intended conditions, the sludge was treated in a laboratory autoclave at 121 °C for 18 minutes, followed by oven drying at 105 °C for 24 hours. The organic matter content of the sludge was determined after this process.

2.3 Mortar Specimens

The specimens were produced with tap water, sand with a grain size of 0.4 mm and limestone Portland cement. All the specimens were produced following the same concentrations of sand and water (54% and 14 %, respectively). The cement was replaced at 0, 3, 5, 7, and 10% by ground sludge treated in each of the methodologies cited above.

The experimental specimens were fabricated, cured, and preserved according to the specifications outlined in EN 1015-11:2019 for construction materials testing [24].

2.4 Mechanical Tests

The mortars were tested after 7-day age of curing and 28-day age of curing. The mortar's mechanical performance was assessed through strength testing, specifically via compressive and flexural analyses. Both tests were conducted on the prepared specimens following the guidelines established in EN 1015-11:2019 [24].

Flexural strength was assessed by applying a load at the midpoint of the specimen until fracture, followed by compressive strength testing through progressive loading 4 cm from each end until maximum resistance was reached.

Axial compression data were statistically evaluated using one-way ANOVA, followed by Tukey's HSD test to compare group means at a 95.0% confidence level. All analyses were conducted using STATGRAPHICS Centurion software.

According to EN 998-1, mortar is classified into four compressive strength categories (CS I to CS IV), determined after 28 days of curing [25]. The compressive strength varies in the range 0.4 to 2.5 MPa, 1.5 to 5.0 MPa, 3.5 to 7.5 MPa and more than 6 MPa for categories CS I to CS IV, respectively [25].

2.5 Economic Viability

The economic viability was evaluated according to the energy costs of each methodology in the preparation of the sludge, and the amount of cement replacement by sludge represents the energy savings/expenditure in the energy balance of the mortar. The calculation of the savings or replacement costs is given by Equation 2.

$$A = B - (B c) + (D e) \quad (2)$$

where

A economy or cost (kWh ton⁻¹ cement)

B energy expenditure of tonne cement production (kWh ton⁻¹ cement)

c cement concentration (fraction)

D energy expenditure in the treatment of tonnes of sludge (kWh ton⁻¹ sludge)

e concentration of sludge (fraction)

Previous research has reported energy consumption values for both sludge treatment and cement manufacturing, as summarised in Table 1.

Tab. 1. Energy requirements for cement production and sludge treatment.

Process	Energy consumption
Cement production	102 kWh ton ⁻¹ cement [26]
Drum or fluidised bed dryers	0.07 kWh kg ⁻¹ H ₂ O [27]
Drying operation	39 kWh ton ⁻¹ dry sludge [28]
Dry sludge and incineration	275 kWh ton ⁻¹ dry sludge
	- 1024.5 kWh ton ⁻¹ dry sludge (recovery) [28]
Co-incineration	- 250 kWh ton ⁻¹ of dry sludge (recovery) [29]

3. Results and Discussion

3.1 Sludge Characterisation

Characterisation of the sludge revealed a pH of 7.8, a moisture content of 83.2% ± 0.2%, total solids (TS) of 16.8% ± 0.2%, and an organic matter (OM) content of 20.7% ± 4.4%.

A pH value between 7 and 8 indicates that it has not been chemically stabilized with liming products such as calcium carbonate [30]. The moisture content observed in the sludge aligns closely with the typical ranges reported in the literature, confirming the consistency of the sample's physical characteristics with previously documented findings [4]. The OM found was low, indicating that the processed sludge had been stabilized, which is consistent with the neutral pH value [15]. The TS was in agreement with literature [31]. TS and moisture are related to the efficiency of the dehydration process to which the sludge was submitted, and it can be said that the low value of OM is related to the good efficiency of the digesters.

3.2 Sludge Preparation

From the M1 preparation methodology, it was assumed that all water had been removed, and thus, the M1 moisture was 0%. Fig. 1a shows the sludge used in this study.

Apart from other factors, the temperature of the environment influences the drying of sludge during solar exposure. During the exposure period, M2 and M3 recorded average temperatures of 14.1 °C and 21.3 °C, respectively, with corresponding average maximums of 18.2 °C and 23.6 °C, and minimums of 11.5 °C and 19.8 °C. Fig. 1(b) and (c) show the system formed during sludge drying. At the end of the exposure period, the sludge retained 5.5% residual moisture in M2 and 4.0% in M3.

Figures 1d and 1e show the sludge before and after burning, respectively.

Fig. 1 (f, g, h) shows the system formed for wet oxidation, in Fig. 1f there is one of the sludge samples in the format as it was autoclaved, its appearance after the autoclave process is shown in Fig. 1g and its appearance after drying in an oven is shown in Fig. 1h. Autoclaving the sludge was an attempt to oxidize organic matter; however, under milder conditions, using the equipment available. The effectiveness of the process was evaluated by determining that the organic matter after autoclaving was $16.50\% \pm 1.32\%$, showing a 27% reduction in organic matter.

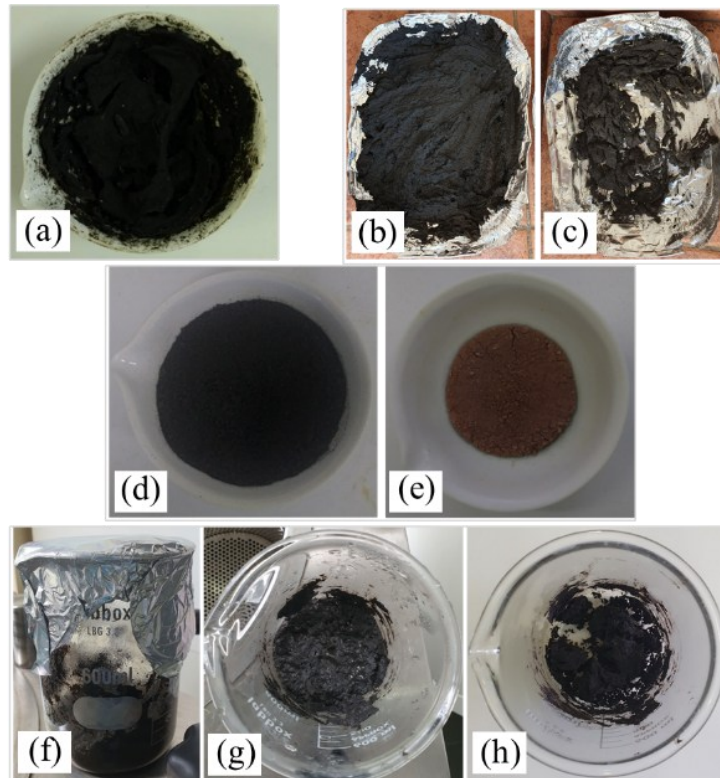


Fig. 1. Sludge preparation for different methodologies

3.3 Mortar Specimens

Mechanical Tests

The tests were intended to identify the changes that occurred when the treated sludge particles were incorporated into the concrete mortar. Fig. 2 shows the final flexural strength of the specimens for each methodology. Fig. 3 shows the average final compressive strength obtained from the specimen using each methodology. The vertical lines show the standard deviations of the measurements.

Analysis of variance (ANOVA) was performed by simple ANOVA, considering each mortar preparation procedure and the concentration of a different treatment for making the mortar; thus, 48 observation points were analyzed at 24 levels. Homogeneous groups created according to Tukey's test are arranged by lowercase letters in Fig. 3.

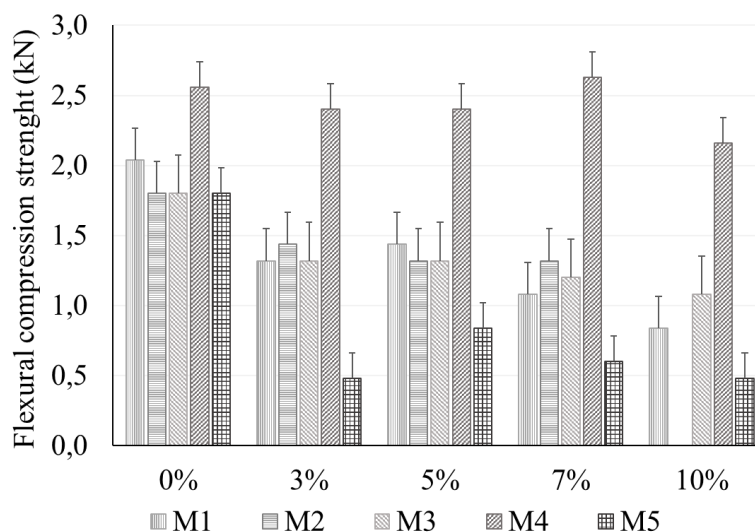


Fig. 2. Flexural strength at 28 days curing for each treatment and substitution concentration.

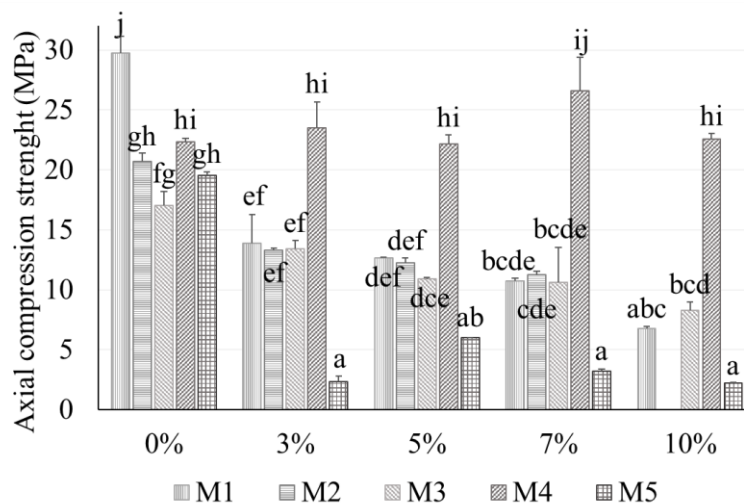


Fig. 3. Axial compressive strength at 28 days curing for each treatment and substitution concentration, with grouping based on Tukey's multi-comparison test ($p \leq 0.05$).

The results indicated that only one specimen exhibited higher mechanical strength compared to the standard specimen, with 7% M4. Specimens made with dry sludge displayed comparable strength values and similar resistance loss patterns, whereas those incorporating M5 yielded the poorest performance.

Fonseca [32] also made mortar specimens replacing cement with dry sludge, but the results were different. For the 5% concentration, there was an improvement in the resistance to both flexion and compression compared to the standard [32]. The specimen with 10% concentration was very close to the standard in the flexural strength test; however, in the compressive strength test, the result was 27% lower than the standard [32].

In the work of Ingunza et al. [33], the flexural and compressive strengths of all samples obtained from sludge ash addition showed higher mechanical resistance than the standard mortar. The author also replaced part of the cement mass with sludge ash; however, at concentrations of 0, 5, 10, 15, and 20% [33].

Despite the reduction in flexural strength with increasing sludge content, the best performance was observed at a 5% concentration using dry sludge (M1 and M3) or M5. In a study by Fonseca [32], the best flexural strength results were obtained at a concentration of 5%. In contrast with M4, the ideal concentration was 7%. In the work of Ingunza et al. [33], the greatest flexural strength was obtained with 20% ash; however, tests with higher concentrations were not performed to determine whether this is the ideal maximum concentration.

The variations in standard values across methodologies may stem from changes in the cement caused by storage conditions after bag opening, as well as inconsistencies in the quality of the sand used.

Two additional statistical analyses were conducted on the compressive strength data. In the first, sludge concentration was not considered, and the results were grouped solely based on the treatment method applied to the sludge. In the second, the preparation method was disregarded, and the data were analysed according to sludge concentration in the mortar. Homogeneous groups identified by Tukey's test ($p \leq 0.05$) are indicated in Table 2 using lowercase letters.

Tab. 2. Homogeneous groups identified using the Tukey multi-comparison test ($p \leq 0.05$) within which there were no statistically significant differences.

Treatment	Average (MPa)	Concentration (%)	Average (MPa)
M5	3.44 a	10	9.95 a
M3	10.81 b	7	12.49 a
M1	11.00 b	5	12.80 a
M2	12.26 b	3	13.28 ab
M4	23.70 c	0	21.87 b

The analysis of the influence of the treatment on the mechanical strength acquired by the mortar (second column of table 2) shows that the M5 treatment to which the sludge is subjected impairs the strength of the mortar produced. The drying methods (M1 – M3) were similar, as they were part of the same homogeneous group (b). M4 proved to be a highlighted method, as it obtained the highest average resistance in a distinct homogeneous group.

The analysis of cement replacement concentration with treated sludge (fourth column of Table 2) revealed that concentrations ranging from 3% to 10% are statistically similar, forming the same homogeneous group (a), while the 3% replacement also showed similarity to the standard (0%).

Dry Sludge (M1 – M3)

Combining the residual moisture data from the sludge drying methods, the mechanical resistance of the mortar and the homogeneous groups obtained show that drying the sludge in the sun does not confer chemical alterations to the material because the moisture content of the particles changes from one formulation to another. This discussion highlights that when drying the sludge under sunlight, the quality of the resulting mortar remains consistent with that produced using oven-dried sludge, provided that the drying system is efficient and climatic conditions are favorable.

All mortars containing dry sludge particles exhibit a compressive strength exceeding 6 MPa, classifying them as category CS IV [25]. These mortars are suitable for general-purpose rendering, colored rendering, and one-coat rendering for exterior use,

though additional parameters like dry bulk density, adhesion, and capillary water adsorption must also be determined for these applications [25].

Sludge Ash (M4)

All mortars made with M4 particles were classified as CS IV [25].

According to research conducted by Paschoalino et al. [34], cement is not hardened by drying, but by a chemical hydration reaction. Several factors influence the mechanical strength of mortar, quality of the clinker, water/cement ratio, content and quality of the aggregates, and dosage of hydroxide calcium [34].

According to Lynn et al. [9], burning sludge at 900 °C increases the amorphous content of the final solid material, which increases pozzolanic activity. The increase in pozzolanic activity is related to the formation of oxides during burning, and the main oxides in M4 are silicon oxide, aluminum oxide, and calcium oxide [9]. Pozzolanic activity involves the binding of lime with water, leading to the formation of water-insoluble calcium silicates [15]. Thus, although the addition of sludge negatively influences the fluidity of the mixture by absorbing water and extending the hardening time, it can contribute to increasing the compressive strength of the mass [15].

Hagemann et al. [22] evaluated the strength activity index to study the pozzolanic activity of the WWTP ash in the replacement of cement in mortars. The authors observed that there is a maximum percentage of the incorporation of sludge ash from WWTP, which starts from a decrease in compressive strength [22].

Aishwarya and Suresh [35] replaced cement and fine aggregates with rice husk ash and waste foundry sand in the production of concrete. In their results, the compressive strength in the replacement with 10% rice husk ash revealed a peak of greater resistance compared with the standard and concentrations of 5, 15, 20%, and 25% [35]. Fonseca [32] reported that the peak compressive strength occurred at a 5% cement replacement by sludge ash in mortars. In the study by Kaish et al. [36], the peak was 15%. In the work of Naamane et al. [37], the peak was 5% for mortars with ash prepared at 700 and 800 °C.

Considering the experiences of the authors mentioned above, the form of cement hardening highlighted by Paschoalino et al. [34], and the conclusions of the studies carried out by Hagemann et al. [22], the peak mechanical resistance at 7% of cement replacement by sludge ash may represent the ideal replacement concentration.

Wet Oxidized Sludge (M5)

With M5 sludge, at 3 and 10% substitution, the mortar can be classified as CS I and II according to the compressive strength acquired at the 28-day curing age. At 5% concentration, they were classified as CS III and IV. At 7% concentration, it only fits the CS II category [25].

By analyzing the performance of mechanical resistance and comparing it with mortars with just dried sludge particles, it can be inferred that during the autoclaving process, the sludge undergoes chemical changes that result in mortars with less flexural and compressive strength.

3.4 Cost-effectiveness

In 2017, the global cement industry consumed approximately 100 kWh of electrical energy per ton of production, a figure reflecting its status as one of the most energy-intensive sectors. While the provided sources do not explicitly confirm stability since 2012, they highlight ongoing challenges related to energy efficiency and resource consumption in cement manufacturing [26]. According to Cochez and Nijs [38], the efficiency and type of cement production process causes the electricity demand to vary from 90 to 150 kWh ton⁻¹ cement. The thermal energy demand for cement production is approximately 3.38 GJ ton⁻¹ clinker. In studies developed by Cochez and Nijs (2010), it was concluded that cement production requires approximately 3.38 GJ of thermal energy per tonne of clinker produced [38].

A literature review by Schnell et al. [27] reports that drum or fluidized bed dryers, which use conduction and convection (via hot gases or steam) to transfer heat to the sludge, consume around 0.07 kWh per kilogram of water removed. As for each ton of dry sludge, it is necessary to evaporate 777 kg H₂O (83.2% to 5.5% humidity), the electric energy demand in this process is 54.4 kWh ton⁻¹ dry sludge.

Two endpoints (3 and 10%) were applied in the calculations of economic viability for mortar production under the conditions studied.

In these scenarios, the electricity consumption for the portion corresponding to cement in the mortar is 100.6 kWh.t⁻¹ cement for the concentrations of 3% and 97.2 kWh ton⁻¹ cement for 10%. Considering the value of 102 kWh ton⁻¹ cement to produce cement and considering equation B, energy savings would be 8.6 kWh ton⁻¹ cement to replace 10% of dry sludge in a dryer or 2.6 kWh ton⁻¹ cement to replace 3%.

Still in this sense, if the sludge is dried with the sun, where considering that there is no energy expenditure, the saving would be 3.1 kWh ton⁻¹ cement for the concentration of 3% and 10.2 kWh ton⁻¹ cement for 10%.

According to the data collected by Xu et al. [28], the drying operation consumes 39 kWh ton⁻¹ dry sludge and 1.53 kJ ton⁻¹ dry sludge, and incineration consumes 275 kWh ton⁻¹ dry sludge, but the operation has an energy recovery of 1024.5 kWh ton⁻¹ dry sludge. In the drying process, with data from Xu et al. [28], there is a consumption of 100.1 kWh ton⁻¹ cement (3%) and 95.7 kWh ton⁻¹ cement (10%) for the proportion of cement with sludge in mortars. Therefore, the electric savings are 1.9 kWh ton⁻¹ cement (3%) and 6.3 kWh ton⁻¹ cement (10%) due to the incorporation of dry sludge in mortars. In the incineration process, electrical consumption is 76.5 kWh ton⁻¹ cement (3%) and 16.9 kWh ton⁻¹ cement (10%) for the cement fraction in mortars with sludge ashes. The reduction in consumption represents savings of 25.5 kWh ton⁻¹ cement (3%) and 85.2 kWh ton⁻¹ cement (10%) in the production of mortars.

Lundin et al. [29] reported that the co-incineration of WWTP sludge with waste generated 2300 kWh of district heating and 250 kWh of electricity per tonne of dry sludge through combined heat and power production. In this scenario, electrical consumption is 91.4 kWh ton⁻¹ cement (3%) and 66.8 kWh ton⁻¹ cement (10%) for the proportion of cement in mortars with sludge ashes. The use of ash represents savings of 10.6 kWh ton⁻¹ cement (3%) and 35.2 kWh ton⁻¹ cement (10%).

The calculated energy savings for each process are summarised in Table 3.

Tab. 3. Energy requirements for cement production and sludge treatment.

Process	Electricity demand	Energy saving (kWh ton ⁻¹ cement)	
		3%	10%
M5	0.07 kWh kg ⁻¹ H ₂ O [27]	2.6	8.6
M3	39 kWh ton ⁻¹ dry sludge [28]	1.9	6.3
M1	0	3.1	10.2
M2	-749.5 kWh ton ⁻¹ dry sludge [28]	25.5	85.2
M4	-250 kWh ton ⁻¹ dry sludge [29]	10.6	35.2

4. Conclusion

The mechanical quality of mortar specimens incorporated with WWTP sludge was tested to study the technical feasibility of the practices. From the comparison of energy production costs between cement production and the methodologies for preparing sludge for subsequent application in mortars, the economic valuation of practices was also evaluated.

From the discussions on energy expenditure, the properties of the sludge obtained at the Bragança WWTP Exhibit considerable suitability for construction-related applications. The low moisture and organic matter content contributes to the energy savings of sludge preparation processes, whether in incineration or drying.

The use of sludge ash at small concentrations did not alter the mechanical strength of the mortar; at a concentration of 7% substitution of cement for ash, the mechanical quality increased in comparison with the standard mortar.

While the drying method (sun vs. oven) did not affect the quality of the mortar produced, it did influence the moisture content of the sludge. The incorporation of sludge reduces the mechanical strength of the mortar with respect to the standard mortar; however, even at concentrations of up to 10%, this loss of strength does not cause the mortar to be classified at a lower resistance than the standard mortar.

The practices of burning and drying the sludge obtained results that justify the procedures and the subsequent application in the mortar with the potential for energy savings while autoclaving the sludge proved not to be interesting for civil application.

Based on these results, wastewater treatment plant sludge performed well as a resource for the production of eco-friendly mortars, incorporating sustainability in civil construction and extending the sludge's useful life to a safe and stable destination.

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