detritus | Multidisciplinary Journal for Circular Economy and Sustainable Management of Residues

CISA

INCORPORATING INDUSTRIAL WASTES INTO MORTAR MIX PRODUCTION: A STEP TOWARDS SUSTAINABLE CONSTRUCTION

Nemesio Daza-Marquez [1,*], Andrés Guzmán [2], Yoleimy Ávila [3], Joaquín Abellán-García [2], Andrea Castro [2] and Marielena Molinares [4]

[1] *Department of Civil Engineering, Universidad Simón Bolívar, Barranquilla, Colombia*
[2] *Department of Civil and Environmental Engineering, Universidad del Norte, Barranquilla, Colombia*
[3] *Instituto Superior de Engenharia de Lisboa, Universidade de Lisboa, av. Rovisco Pais, 1049-001 Lisboa, Portugal*
[4] *Department of Mechanical Engineering, Universidad del Norte, Barranquilla, Colombia*

Article Info:
Received:
16 July 2024
Revised:
10 October 2024
Accepted:
11 November 2024
Available online:
24 January 2025

Keywords:
Mortar
Water treatment plant sludges
Nitrophosphogypsum
Mineral admixtures

ABSTRACT

The incorporation of calcined sludge (CS) from water treatment plants and nitrophosphogypsum (NPG) into mortar mixtures has been investigated as a potential strategy to reduce the consumption of ordinary Portland cement (OPC) and subsequently lower the carbon footprint of construction materials. Two scenarios were subjected to analysis: in the first, CO_2 emissions resulting from the treatment of NPG and CS were considered; in the second, emissions were considered negligible due to the reduced energy demand of waste treatment processes compared to OPC production. The chemical composition and mechanical properties of the mortars were evaluated through the use of X-ray fluorescence (XRF) and compressive strength testing. The mortar mixtures were prepared with a water-to-binder ratio of 0.485 in accordance with the ASTM standards. The mortar mixture containing 5% NPG and 5% CS exhibited a 6.65% increase in compressive strength, reaching 38.96 MPa after 90 days. Despite a slight reduction in early strength, long-term performance was enhanced by the formation of additional calcium silicate hydrates. Regarding sustainability, a reduction of 62.06 kg CO_2 per cubic meter of mortar was achieved in both scenarios, with more substantial reductions in Scenario 2. These results show that incorporating NPG and CS supports the circular economy by utilizing industrial by-products and provides a sustainable alternative to OPC, significantly reducing CO_2 emissions while maintaining or enhancing mechanical performance, thereby aligning with global efforts towards eco-friendly construction practices.

1. INTRODUCTION

In the Colombian Caribbean region, there are raw materials with high potential as mineral admixtures or partial replacements for Portland cement (OPC). When implemented in mortar mixes, these materials exhibit performance similar to traditional mixes due to their chemical and mechanical properties (Bohórquez González et al., 2020; Palma & Sierra, 2011). The sludges from water treatment plants (WTPS) are residues from the water purification process, studied for their potential (Chang et al., 2020). According to a report by the WTP company of Atlántico, Colombia, an average of 8.6 m^3/s is drawn from the Magdalena River (AAA, 2024; Superintendencia de Servicios Públicos Domiciliarios, 2023). Torres-Lozada et al. (2022) determined that the production of sludge, based on the volume of treated water, can range between 2% and 5%. The cited values are contingent upon the specific materials required by the treatment process at each facility. Based on a sludge production rate of 3%, it can be estimated that approximately 7,681,125 cubic meters of sludge are produced annually in the Atlantico department (Colombia) alone.

Several studies have supported the use of WTPS in the construction sector, either as a supplementary cementitious material (SCM) or in combination with other waste materials (Daza & Medina, 2017; Ruviaro et al., 2021; Daza Márquez, 2022; Mahanna et al., 2024). For example, incorporating calcined sludge in mortar mixes was evaluated by He et al. (2023), and a 10% improvement in compressive strength was achieved by adding 10% sludge ash compared to OPC mixes. Additionally, using alum sludge as a partial cement replacement in mortars was investigated by Liu et al. (2022), and enhanced resistance to high temperatures was observed. Mortar mixes containing 20% alum sludge kept higher compressive strength after exposure to temperatures of up to 800°C, surpassing sludge-free mixes by 15%

* Corresponding author:
Nemesio Daza-Marquez
email: nemesiod@uninorte.edu.co

https://doi.org/10.31025/2611-4135/2025.19465

. Similarly, the addition of up to 5% sludge in brick manufacturing was reported by De Carvalho Gomes et al. (2019), resulting in a reduced environmental impact while maintaining satisfactory mechanical properties, demonstrating its viability for use in ceramic materials. These studies indicate the potential of drinking water treatment sludge to improve mechanical properties and durability in construction applications while also contributing to waste reduction and carbon emission mitigation (Z. He et al., 2024).

On the other hand, phosphogypsum (PG), an agro-industrial byproduct from the fertilizer industry, has demonstrated chemical properties that could complement or enhance those found in WTPS for the development of ternary mortar mixes as partial replacements for OPC. Fertilizer production is expected to increase from 47 million tons in 2020 to 49 million tons by 2024, resulting in a rise in the waste generated [2]. The PG-producing industry maintains that its chemical and physical properties make it unsuitable for other industrial sectors, such as construction and agriculture. However, PG has become an essential component of cementitious materials because of its high calcium oxide content (up to 42%) (Rashad, 2017). If converted correctly, the PG byproduct of agro-industrial processes can be used as a substitute raw material for building materials (green technologies). Adding PG to hydraulic mortar mixtures is a promising approach for use. It has been acknowledged as one of the most advantageous ways to dispose of PG because of its low preparation costs and broad use, which align with the global building materials industry's drive toward green and low-carbon growth (Ohji et al., 2017). However, nitrophosphogypsum (NPG), an agro-industrial byproduct of the fertilizer industry, is a kind of phosphogypsum produced in Colombia's Caribbean region and derived from the manufacture of nitrophosphate fertilizer.

In the Atlantico department of Colombia, one fertilizer industry generates an average of 62,000 tons of NPG waste per year (Palma & Sierra, 2011). NPG contains impurities and toxic elements, the majority of which are typically deposited in open landfills for natural degradation, risking potential environmental impact. Due to this method of final disposal, the physical and chemical characteristics of this residue are not fully considered for utilization in the construction sector despite its high content of calcium oxide, a significant compound in the composition of cementitious materials (Rashad, 2017).

The present research evaluates the effectiveness of utilizing calcined residues from water treatment plants (CS) and NPG in mortars for the construction sector, expressed as the percentage of recyclable residue relative to the captured volume at the plant. The primary focus of this research lies in incorporating these residues into a value chain, aiming to contribute to the circular economy by utilizing these materials as sustainable solutions in construction.

1.1 Research significance

Incorporating industrial waste materials, such as WTPS, and agricultural byproducts like NPG into mortar mixtures presents a pivotal step towards sustainable construction. This research highlights that using these materials can significantly reduce CO_2 emissions without compromising the strength or workability of the mortar. These findings motivate the exploration of waste valorization, offering a commercially viable pathway for eco-friendly material development and aligning with global sustainability goals in the construction industry.

2. MATERIALS AND METHODS

This research involved the preparation of cubic mortar samples. The mixing, casting, and curing methods were conducted following the standards outlined in ASTM C305 (2020a), ASTM C109 (2021a), and ASTM C511 (2021b), respectively.

2.1 Mortar mixtures

Four (4) mortar mixtures were formulated, incorporating two (2) types of industrial waste. The first one corresponds to NPG, which, according to the literature, is primarily composed of CaO and SO_3 (Rashad, 2017). On the other hand, the second waste type is associated with CS, with SiO_2, Al_2O_3, and Fe_2O_3 being the primary components (Ruviaro et al., 2021). A fertilizer company from the Colombian Caribbean donated the NPG. It was calcined at 600°C for two hours, crushed, and sieved through a No. 200 sieve (75 microns) (Figure 1). The water treatment sludge was exposed to the sun for 36 hours to eliminate free water. It was then crushed, and the same procedure was followed for the NPG (Figure 2).

The waste materials were considered as a partial replacement for cement at weight-to-weight ratios with replacement proportions of 10%, as estimated according to the existing literature (Calderón-Morales et al., 2021; Chang et al., 2020; Rashad, 2017; Świerczek et al., 2018; Vouk et al., 2017). Both wastes underwent thermal treatment at temperatures of 600°C for 2 hours. The elemental chemical composition of CS and NPG, obtained through XRF analysis, along with their physical properties, is summarized in Table 1. XRF analysis was conducted on the Vanta M Series Handheld instrument. The NPG is primarily composed of SO_3 (52.74%) and CaO (39.8%), with minor amounts of SiO_2, Al_2O_3, Fe_2O_3, and MgO. In contrast, the CS material has a high content of SiO_2 (61.59%) and Al_2O_3 (21.36%), with minor amounts of Fe_2O_3 (10.09%), MgO, and other components.

Scanning Electron Microscopy (SEM) analysis of NPG revealed the presence of elongated, prismatic particles with adhered impurities. These particles were subjected to thermal treatment, resulting in their reduction (Figure 3) (Rashad, 2017; Godoy et al., 2019; Daza-Marquez et al., 2024). In contrast, the SEM images of CS revealed needle-like shapes with porous and inhomogeneous surfaces, particularly in agglomeration areas. The control of particle size resulted in an improvement in the homogeneity of NPG, whereas CS exhibited localized porosity (Figure 4) (Husillos Rodríguez et al., 2011).

The fine aggregate used was natural sand from Santo Tomas, Atlántico, with a fineness modulus of 1.98. The average particle size (D50) was 0.425 mm, while the D10, D30, and D60 were 0.268 mm, 0.335 mm, and 0.460 mm, respectively. The uniformity coefficient (Cu) was 1.72, and the

FIGURE 1: Open-pit NPG quarry.

FIGURE 2: WTP sludges.

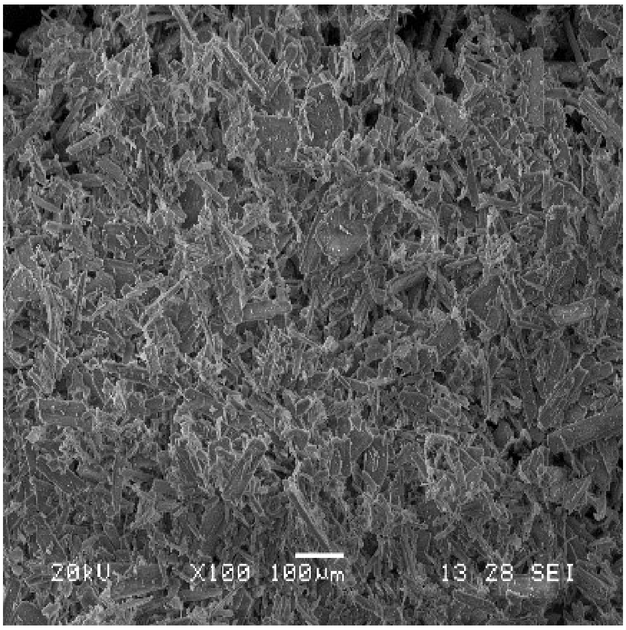

FIGURE 3: SEM images of NPG.

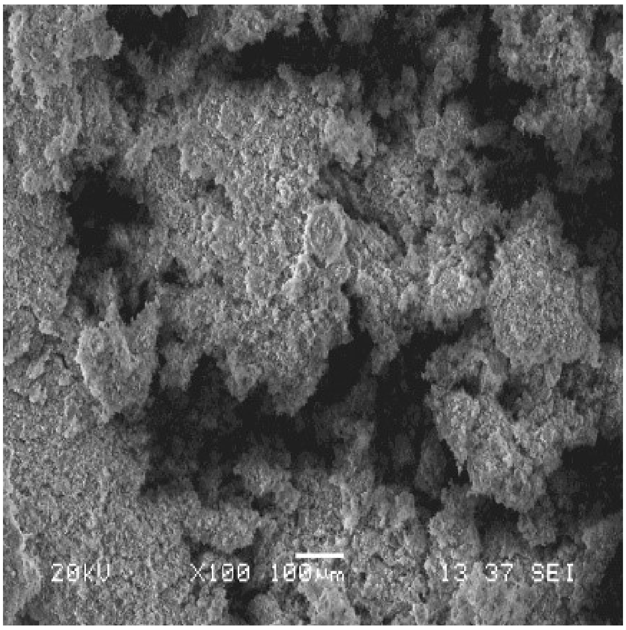

FIGURE 4: SEM images of CS.

gradation coefficient was 0.91. The specific gravity of the sand was 2.61, and its water absorption was 0.78%. These properties comply with the corresponding ASTM standards for sand characterization. The mix was prepared using tap water that met the ASTM C1602M standards (2022).

The quantities of each mortar mixture type are presented in Table 2. These typologies originate from a prior investigation conducted by the researchers (Daza-Marquez et al., 2024; Daza et al., 2023; Daza Márquez, 2022), wherein it was determined that they exhibited optimal mechani-

TABLE 1: Chemical characterization of binders.

Binder	Oxide in %						
	SiO_2	Al_2O_3	SO_3	CaO	Fe_2O_3	MgO	Others
NPG	2.48	0.69	52.74	39.8	0.07	0.18	0.83
CS	61.59	21.36	0.18	1.39	10.09	1.44	3.95

TABLE 2: Quantities of material categorized by type in kg/m³ with a w/b ratio of 0.485 to produce 1 m³ of mortar.

Mix	Sand	OPC	NPG	CS	Water
M0	1833.28	666.65	0.00	0.00	325.84
MN10	1833.28	599.98	66.66	0.00	325.84
MN5C5	1833.28	599.98	33.33	33.33	325.84
MC10	1833.28	599.98	0.00	66.66	325.84

cal performance after 90 days of curing according to the guidelines of ASTM C109 (2021a).

2.2 Experimental methods

Once the mixing process was completed, the workability of the fresh mortars was evaluated according to the standard procedure outlined in ASTM C1437 (2020b). This method, commonly known as the flow table test, measures the consistency and flow of the mortar mix (Figure 5). To evaluate the mechanical performance of the mortars, the compressive strength of mortar cubes with dimensions of 50 mm × 50 mm × 50 mm was tested at intervals of 28 and 90 days according to ASTM C109 (2021a). For each mortar type, three cubes were prepared and tested (Figure 6), with the average compressive strength reported.

2.3 Environmental feasibility and system boundaries

This environmental analysis aims to investigate the environmental impact of producing a mortar mixture using different industrial waste materials as a partial replacement for cement. Through a life cycle analysis, an estimation of CO_2 emissions generated from each of the experimentally proposed typologies for producing 1 m³ of mortar was calculated (functional unit).

In this study, two scenarios were considered. In the first scenario, waste materials (NPG and CS) are commercialized within the construction sector, and their treatment results in an environmental burden due to emissions generated during the drying and calcination processes. In the second scenario, a greater environmental benefit is assumed, where the waste materials are used in a way that results in near-zero emissions due to the lower energy demand of their treatments compared to cement clinker production.

2.3.1 CO_2 evaluation and boundaries

The following parameters were considered: the quantity of material to be treated, treatment method, CO_2 emissions, and performance based on the waste's availability. A cradle-to-gate approach is used to construct the examined system (ISO 14040:2006 (2020)). The system boundaries, illustrated in Figure 7, encompass the raw materials and all subsequent processes, culminating in the mixed mortar at the gate.

The CO_2 emissions arising from each material employed in mortar production were determined using the method reported by Yang et al. (2013), using equation Eq. (1). Where Ce is the total carbon emission of the element or material, $CO_{2\text{-}M}$ is the carbon emissions in the material phase (including the treatment), $CO_{2\text{-}P}$ represents the emissions of the production phase. Emissions associated with material transportation were not considered because of their high variability.

$$C_e = CO_{2-M} + CO_{2-P} \quad (1)$$

CO_2 emissions linked to materials ($CO_{2\text{-}M}$) were calculated using Eq. (2), following reference values of the existing literature. W_i represents the volume unit per weight in kg/m³, while $CO_{2(i)\text{-}LCI}$ is the constant emission in kg per kg of material in $CO_{2\text{-}kg/kg}$.

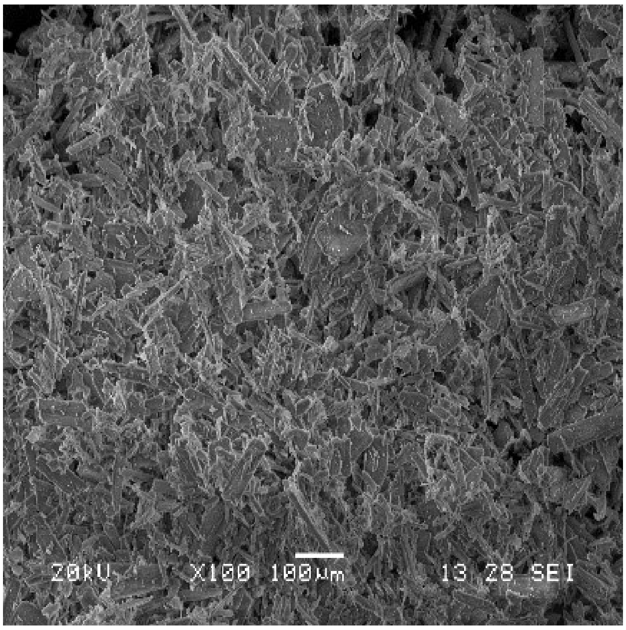

FIGURE 5: Measurement of the slump flow in the mortar.

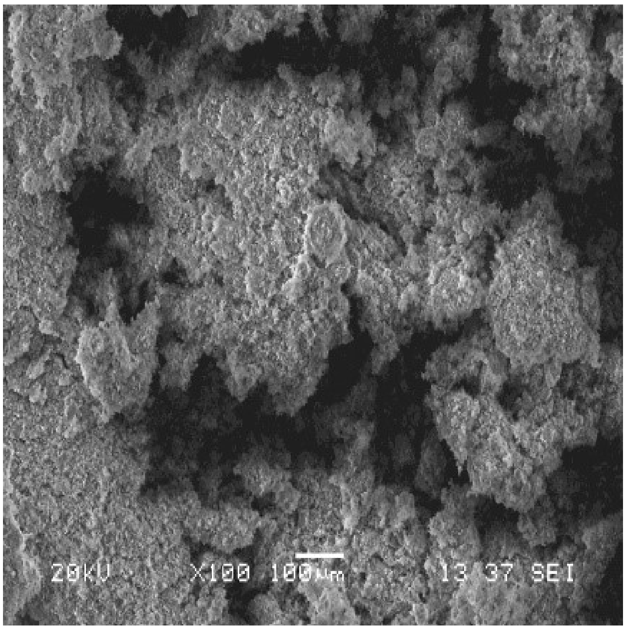

FIGURE 6: Compressive strength assessment setup.

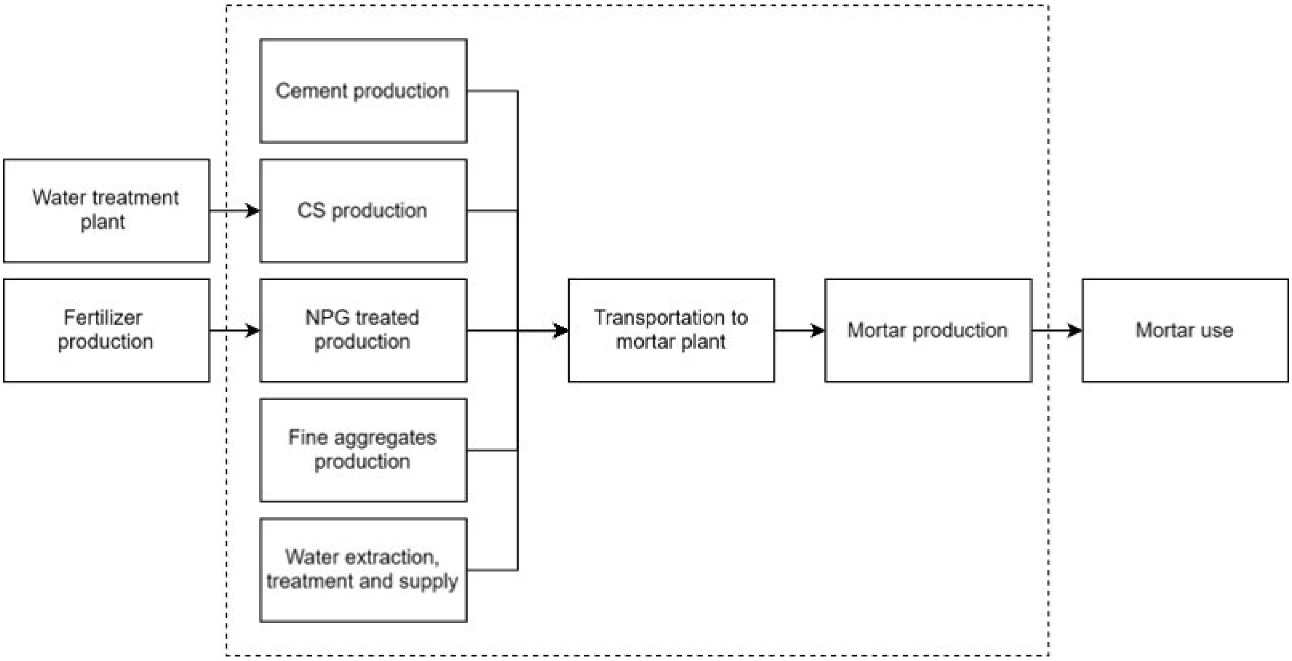

FIGURE 7: System boundaries considered in the environmental analysis.

2-kg/kg.

$$CO_{2-M} = \sum_{i=1}^{n} \left(W_i \times CO_{2(i)-LCI}\right) \quad (2)$$

2.3.2 Data collection

The data utilized to formulate the LCA of raw materials was obtained from peer-reviewed scientific literature. The composition of the mortars from previous studies was used as a reference to assess the environmental impact of mortars containing mining residues. Table 3 outlines the CO_2 emissions (in kg per kg) associated with 1 kg of cement, sand, water, NPG, and CS, along with the corresponding data sources.

3. RESULTS AND DISCUSSION

3.1 Workability and compressive strength

Figure 8 summarizes the workability and compressive strength results for all the mixtures. The control mix (M0) showed the highest workability, with a flow percentage of 131.90%. In comparison, the mix with 10% NPG (MN10) had a 3.44% reduction in flowability, achieving a flow of 127.37%. This reduction likely occurs because of NPG absorbent properties, which reduce the free water available for cement hydration. Its porous nature increases the water demand, limiting the mobility of the mortar during mixing (Bhadauria & Thakare, 2006; Rashad, 2017).

The MN5C5 mixture, containing 5% NPG and 5% CS, experienced a more pronounced decrease in flowability, with a value of 115.48%, reflecting a 12.48% drop compared to M0. This significant reduction in workability likely results from the combined effects of both supplementary SCMs. Their porous nature causes them to absorb more water, limiting the free water available for cement particle dispersion and hydration. These findings align with previous studies where highly porous SCMs like NPG and calcined sludge reduced workability by absorbing excess water (Chen & Poon, 2017). On the other hand, the MC10 mixture, with 10% CS, also showed reduced workability, achieving a flow of 117.51%, representing a 10.90% decrease compared to the control sample. As in MN5C5, the porous structure of CS increases the water demand, negatively affecting the mortar's flowability (Krejcirikova et al., 2019).

The M0 achieved a compressive strength of 36.53 MPa. A 9.41% reduction in compressive strength, reaching a value of 33.09 MPa, was observed in the MN10 mix containing 10% NPG. This decrease in strength is attributed to the reduced reactivity of nitrophosphogypsum, delaying the formation of C-S-H during the hydration process (Alaghebandian et al., 2020). Furthermore, the crystalline structure of NPG is believed to limit the development of strong bonds within the cement matrix, negatively affecting the mechanical properties of the mortar. In contrast, the MN5C5 mix, with 5% NPG and 5% calcined sludge, achieved the highest compressive strength, with a value of 38.96 MPa, representing a 6.65% increase compared to the control sample. It is suggested that the combination of NPG and calcined sludge in these proportions enhanc-

TABLE 3: CO_2 emissions per material for mortars.

Material	CO_2-kg/kg	References
Cement	0.9310	(Yang et al., 2015)fly ash (FA
Sand	0.0026	(Yang et al., 2015)fly ash (FA
Water	1.96× 10^{-4}	(Yang et al., 2015)fly ash (FA
NPG	0.1414*	(Nana et al., 2023; Lv et al., 2024)
SC600	0.0356*	(Huang et al., 2024; Lv et al., 2024)

** The corresponding value already includes solar drying, calcination, and crushing emissions.*

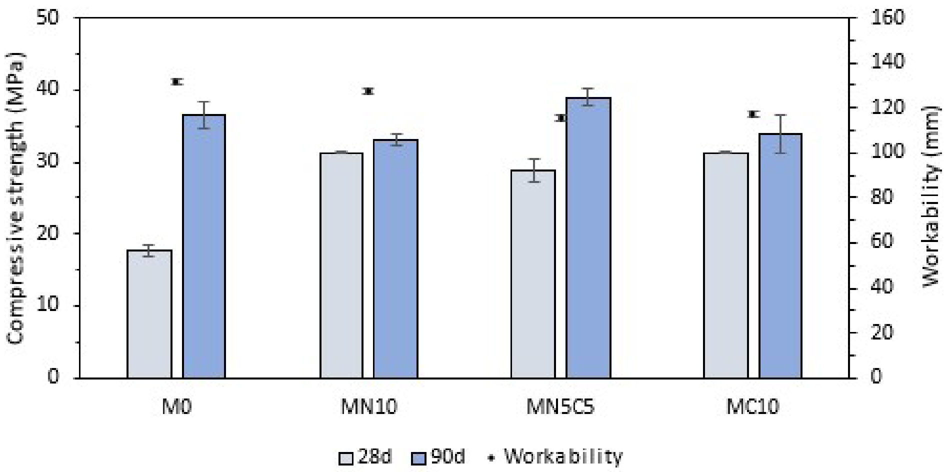

FIGURE 8: Workability and compressive strength in mortar mixtures.

es the long-term mechanical performance of the mortar. The high reactivity of calcined sludge likely accelerated the formation of additional C-S-H, contributing to the improved compressive strength observed at 90 days (Hewlett & Liska, 2019; Lothenbach et al., 2011).

A compressive strength of 33.83 MPa was recorded for the MC10 mix, containing 10% CS, showing a reduction of 7.39% compared to M0. While calcined sludge is highly reactive, it is believed that the partial substitution of cement with 10% calcined sludge reduced the available portlandite (CH) for reaction, thus limiting the formation of C-S-H and negatively affecting the compressive strength of the mortar.

3.2 Environmental feasibility

It is essential to determine the quantity of each material required per cubic meter of mortar, measured in the same units. In total, 666.65 kg/m^3 of OPC is necessary to produce 1 m^3 of traditional mortar with a water-to-cement ratio of 0.485. The relationships between quantities and CO_2 emissions in kg/kg and kg/m^3, based on the specified dosages by type (Table 2), are presented in Table 4.

For scenario 2, it is noteworthy that, because of the thermal treatment applied to mineral admixtures (at temperatures of 105°C and 600°C), which is lower than the clinkerization temperature of cement (approximately 1350°C), and with only 24 hours and 2 hours required for the drying and calcination processes, respectively, the CO_2 emissions for NPG and CS approached zero (Jacoby, 2020). It is important to highlight that, since both waste materials are currently being studied for their potential use in the construction sector and are not yet commercialized, the environmental impact (i.e., CO_2 emissions, renewable energy sources) is attributed to the primary process that generates these wastes (Almusaed et al., 2024).

TABLE 4: CO_2 emissions (kg/kg) of each material used in mortar mixes.

Mix	Sand	Cement	NPG[(a)]	CS[(a)]	Water	Total
M0	4.77	620.65	0.00	0.00	6.39×10^{-2}	625.48
MN10	4.77	558.58	9.43	0.00	6.39×10^{-2}	572.84
MN5C5	4.77	558.58	4.71	1.19	6.39×10^{-2}	569.31
MC10	4.77	558.58	0.00	2.37	6.39×10^{-2}	565.79

[(a)] *The CO_2 emissions generated by waste are close to zero in scenario 2.*

Once the CO_2 emissions per type of material are known based on their dosage, the next step involves calculating the total emissions released to produce one cubic meter of mortar according to the mix typology. The results obtained from both scenarios are presented in Figure 9. Mix typologies formulated with NPG and CS contribute to reducing at least 62.06 kg of CO_2 for each cubic meter of prepared mortar.

In Scenario 1, which incorporates CO_2 emissions from the processing of NPG and CS based on the values presented in the literature, a notable reduction in emissions is observed as the cement content is diminished. The highest emissions were observed in the control mix, designated as M0, with 625.48 kg of CO_2 equivalent. The primary source of these emissions was identified as the cement. A reduction to 572.84 kg CO_2 is achieved in mix MN10, where 10% of the cement is replaced by NPG, a reduction of 8.4%. The MN5C5 mix, which contains 5% NPG and 5% CS, further reduces emissions to 569.31 kg CO_2. The most significant reduction is observed in MC10, where replacing 10% of the cement with CS reduces emissions to 565.79 kg CO_2, a 9.5% reduction compared to the control. Overall, substituting cement with NPG and CS, especially CS because of its lower emission factor, results in significant CO_2 reductions. In Scenario 2, where CO_2 emissions from NPG and CS are considered negligible because of their processing methods, total emissions are further reduced compared to Scenario 1. The control mix (M0) remains unchanged at 625.48 kg of CO_2, as no alternative materials are introduced. However, for MN10, MN5C5, and MC10, the emissions decrease uniformly to 563.41 kg of CO_2, representing an additional reduction compared to Scenario 1. This consistent reduction across the modified mixes highlights the significant environmental benefit of incorporating NPG and CS, especially when their emissions are minimized (Singh et al., 2023).

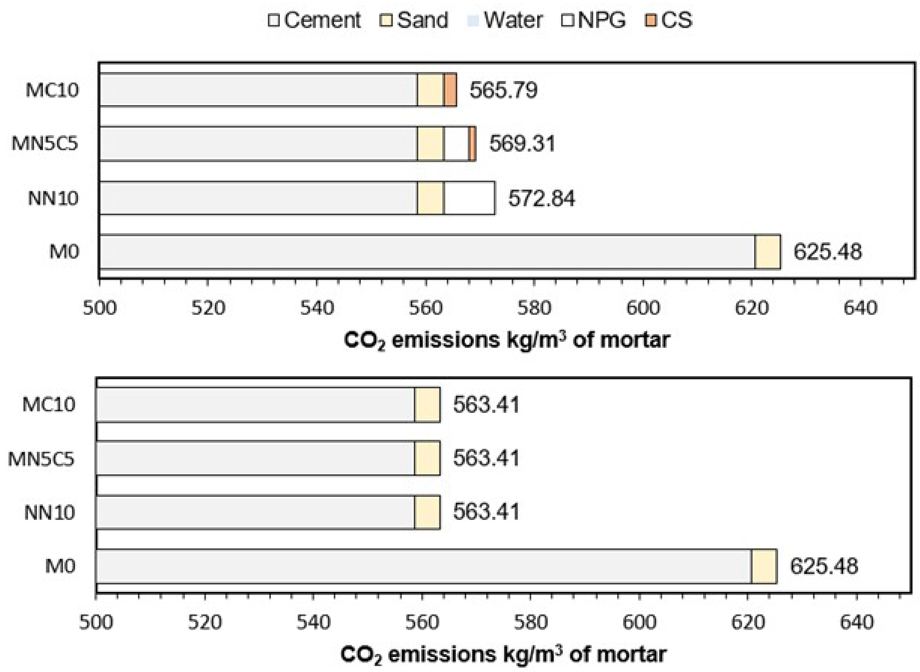

FIGURE 9: CO_2 Emissions based on mixed typology (a) scenario 1 (b) scenario 2.

By correlating the environmental benefits of incorporating each of the proposed mortar samples with the mechanical properties of masonry mortars, it could be established that the simultaneous and individual implementation of NPG and CS does not significantly affect the properties of traditional mortar. Furthermore, it represents an environmental advantage in terms of CO_2 emissions into the atmosphere.

4. CONCLUSIONS

The present study investigates the potential use of CS from water treatment plants and NPG as partial replacements for OPC in mortar mixtures, with a particular emphasis on enhancing environmental sustainability. The following conclusions were derived from the study:

All proposed mortar typologies exhibited comparable compressive strength values to the control sample at 90 days, with an average strength of 35.64 MPa across the different mixes. The compressive strength at early ages exhibited a range of results, with reductions of 7.39% and increases of 6.65% compared to the control sample. Although there are slight variations in mechanical performance, the environmental benefits of reduced CO_2 emissions and waste utilization make these differences worthwhile.

Although there were slight reductions in early strength, the mixture comprising 5% NPG and 5% CS exhibited a 6.65% improvement in compressive strength at 90 days, suggesting long-term performance comparable to traditional OPC mixtures. From an environmental perspective, Scenario 1 (which accounts for CO_2 emissions from NPG and CS processing) resulted in a notable reduction in carbon emissions compared to the control mixture. The environmental impact was further reduced in scenario 2 (where the CO_2 emissions of NPG and CS are considered negligible). This was due to the lower energy demand of processing NPG and CS compared to the production of OPC. This demonstrates that, despite slight mechanical variations, these industrial byproducts maintain the mechanical integrity of the mortar while significantly lowering its carbon footprint. This offers a more sustainable solution in both processing scenarios.

The utilization of CS and NPG contributes to the circular economy by enhancing the value of industrial by-products, minimizing waste, and promoting sustainable construction practices without compromising the mechanical performance of cement mortars.

Overall, the findings highlight that CS and NPG are viable alternatives to OPC in mortar mixtures in the Caribbean region of Colombia, offering both environmental and technical advantages. Further research is required to optimize these materials for maximum sustainability benefits.

ACKNOWLEDGEMENTS

The authors express gratitude to MinCiencias for its support in advancing and elevating the standard of education in Colombia through the promotion of high-quality initiatives (MinCiencias Call 809).

REFERENCES

AAA. (2024). Informe de gestión y sostenibilidad 2023 (p. 240). AAA.

Alaghebandian, N., Mirvalad, S., & Javid, A. A. S. (2020). Durability of self-consolidating concrete and mortar mixtures containing ternary and quaternary cement blends exposed to simulated marine environment. Construction and Building Materials, 259, 119767. https://doi.org/10.1016/j.conbuildmat.2020.119767

Almusaed, A., Yitmen, I., Myhren, J. A., & Almssad, A. (2024). Assessing the impact of recycled building materials on environmental sustainability and energy efficiency: A comprehensive framework for reducing greenhouse gas emissions. Buildings, 14(6), 1566. https://doi.org/10.3390/buildings14061566

ASTM International. (2020a). ASTM C305-20: Standard Practice for Mechanical Mixing of Hydraulic Cement Pastes and Mortars of Plastic Consistency. ASTM International. 10.1520/C0305-20

ASTM International. (2020b). ASTM C1437-20: Standard test method for flow of hydraulic cement mortar. ASTM International. https://www.astm.org/Standards/C1437

ASTM International. (2021a). ASTM C109/C109M - 21: Standard Test Method for Compressive Strength of Hydraulic Cement Mortars (Using 2-in. Or [50-mm] Cube Specimens). ASTM International. https://doi.org/10.1520/C0109_C0109M-21

ASTM International. (2021b). ASTM C511-21: Standard Specification for Mixing Rooms, Moist Cabinets, Moist Rooms, and Water Storage Tanks Used in the Testing of Hydraulic Cements and Concretes. ASTM International. https://doi.org/10.1520/C0511-21

ASTM International. (2022). ASTM C1602M-22: Standard Specification for Mixing Water Used in the Production of Hydraulic Cement ConcreteStandard Specification for Mixing Water Used in the Production of Hydraulic Cement Concrete. ASTM International. https://doi.org/10.1520/C0511-21

Bhadauria, S., & Thakare, R. B. (2006). Utilisation of phosphogypsum in cement mortar and concrete. 31st Conference on Our World in Concrete & Structures, 9. http://cipremier.com/100031016

Bohórquez González, K., Pacheco, E., Guzmán, A., Avila Pereira, Y., Cano Cuadro, H., & Valencia, J. A. F. (2020). Use of sludge ash from drinking water treatment plant in hydraulic mortars. Materials Today Communications, 23, 100930. https://doi.org/10.1016/j.mtcomm.2020.100930

Calderón-Morales, B. R. S., García-Martínez, A., Pineda, P., & García-Tenório, R. (2021). Valorization of phosphogypsum in cement-based materials: Limits and potential in eco-efficient construction. Journal of Building Engineering, 44, 102506. https://doi.org/10.1016/j.jobe.2021.102506

Chang, Z., Long, G., Zhou, J. L., & Ma, C. (2020). Valorization of sewage sludge in the fabrication of construction and building materials: A review. Resources, Conservation and Recycling, 154, 104606. https://doi.org/10.1016/j.resconrec.2019.104606

Chen, Z., & Poon, C. S. (2017). Comparative studies on the effects of sewage sludge ash and fly ash on cement hydration and properties of cement mortars. Construction and Building Materials, 154, 791–803. https://doi.org/10.1016/j.conbuildmat.2017.08.003

Daza Márquez, N. M. (2022). Evaluación del desempeño mecánico y químico de mortero con inclusión de lodo calcinado a 600°C y nitrofosfoyeso para su aplicación en la construcción [Universidad del Norte]. https://manglar.uninorte.edu.co/handle/10584/10304

Daza, N., Ávila, Y., Guzmán, A., & Abellán-Garcia, J. (2023). Absorption Tests of Binary and Ternary Mortar Mixtures and Their Relationship with Compressive Strength. In C. Chastre, J. Neves, D. Ribeiro, F. F. S. Pinho, H. Biscaia, M. G. Neves, P. Faria, & R. Micaelo (Eds.), Testing and Experimentation in Civil Engineering (pp. 231–241). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-29191-3_20

Daza, N., & Medina, A. (2017). Análisis comparativo del contenido de óxidos presentes en las cenizas de lodos de PTAP y el cemento Portland Tipo uno [Thesis]. Universidad de la Costa.

Daza-Marquez, N., Guzmán, A., Avila, Y., & Abellan-Garcia, J. (2024). Exploring the potential of nitrophosphogypsum and calcined water-treatment plant sludges in mortar mixtures: A study on workability and strength. Construction and Building Materials, 432, 136646. https://doi.org/10.1016/j.conbuildmat.2024.136646

De Carvalho Gomes, S., Zhou, J. L., Li, W., & Long, G. (2019). Progress in manufacture and properties of construction materials incorporating water treatment sludge: A review. Resources, Conservation and Recycling, 145, 148–159. https://doi.org/10.1016/j.resconrec.2019.02.032

Godoy, L. G. G. de, Rohden, A. B., Garcez, M. R., Costa, E. B. da, Da Dalt, S., & Andrade, J. J. de O. (2019). Valorization of water treatment sludge waste by application as supplementary cementitious material. Construction and Building Materials, 223, 939–950. https://doi.org/10.1016/j.conbuildmat.2019.07.333

He, Z., Wang, B., Shi, J., Rong, H., Tao, H., Jamal, A. S., & Han, X. (2024). Recycling drinking water treatment sludge in construction and building materials: A review. Science of The Total Environment, 926, 171513. https://doi.org/10.1016/j.scitotenv.2024.171513

He, Z.-H., Han, X.-D., Jin, J., Li, J., Tang, W., & Shi, J. (2023). Recycling of water treatment sludge in concrete: The role of water-binder ratio from a nanoscale perspective. Science of The Total Environment, 162456. https://doi.org/10.1016/j.scitotenv.2023.162456

Hewlett, P., & Liska, M. (2019). Lea's Chemistry of Cement and Concrete (5th edition). Butterworth-Heinemann. https://www.elsevier.com/books/leas-chemistry-of-cement-and-concrete/hewlett/978-0-08-100773-0

Huang, J., Liu, Z., Wei, X., Ding, X., Zhu, J., Zhao, Y., Iqbal, B., & Guo, S. (2024). Enhancing the Performance of Hemihydrate Phosphogypsum by the Collaborative Effects of Calcium Hydroxide and Carbonation. Materials, 17(10), Article 10. https://doi.org/10.3390/ma17102204

Husillos Rodríguez, N., Martínez-Ramírez, S., Blanco-Varela, M. T., Guillem, M., Puig, J., Larrotcha, E., & Flores, J. (2011). Evaluation of spray-dried sludge from drinking water treatment plants as a prime material for clinker manufacture. Cement and Concrete Composites, 33(2), 267–275. https://doi.org/10.1016/j.cemconcomp.2010.10.020

Jacoby, M. (2020, October 22). Alternative materials could shrink concrete's giant carbon footprint. Chemical & Engineering News, 98(45). https://cen.acs.org/materials/inorganic-chemistry/Alternative-materials-shrink-concretes-giant/98/i45

Krejcirikova, B., Ottosen, L. M., Kirkelund, G. M., Rode, C., & Peuhkuri, R. (2019). Characterization of sewage sludge ash and its effect on moisture physics of mortar. Journal of Building Engineering, 21, 396–403. https://doi.org/10.1016/j.jobe.2018.10.021

Liu, Y., Zhuge, Y., Chow, C. W. K., Keegan, A., Li, D., Pham, P. N., Yao, Y., Kitipornchai, S., & Siddique, R. (2022). Effect of alum sludge ash on the high-temperature resistance of mortar. Resources, Conservation and Recycling, 176, 105958. https://doi.org/10.1016/j.resconrec.2021.105958

Lothenbach, B., Scrivener, K., & Hooton, R. D. (2011). Supplementary cementitious materials. Cement and Concrete Research, 41(12), 1244–1256. https://doi.org/10.1016/j.cemconres.2010.12.001

Lv, T., Zhang, J., Zhao, M., Yang, J., Hou, D., & Dong, B. (2024). Utilization of Sintered Sludge Ash with Different Mechanical–Thermal Activation Parameters as a Supplementary Cementitious Material: Mechanical Properties and Life Cycle Assessment of Cement-Based Paste. Materials, 17(16), 4101. https://doi.org/10.3390/ma17164101

Mahanna, H., Salah, H., Mansour, A., Elareed, A., Abadel, A. A., Nehdi, Moncef. L., & Tahwia, A. M. (2024). Eco-efficient reuse of alum-based water treatment sludge into structural sintering bricks. Case Studies in Construction Materials, 20, e03011. https://doi.org/10.1016/j.cscm.2024.e03011

Nana, B., Zallé, H., Ouarma, I., Daho, T., Yonli, A., & Béré, A. (2023). Assessment of carbon dioxide emission factors from power generation in Burkina Faso. Clean Air Journal, 33(2). https://doi.org/10.17159/caj/2023/33/2.15701

Ohji, T., Matyáš, J., Colorado, H., & Kanakala, R. (2017). Advances in Materials Science for Environmental and Energy Technologies VI. John Wiley & Sons.

Palma, A., & Sierra, K. (2011). Beneficio de nitrofosfoyeso proveniente de la fabricación de fertilizante compuestos para su uso en la industria de la construcción [Thesis].

Rashad, A. M. (2017). Phosphogypsum as a construction material. Journal of Cleaner Production, 166, 732–743. https://doi.org/10.1016/j.jclepro.2017.08.049

Ruviaro, A. S., Silvestro, L., Scolaro, T. P., De Matos, P. R., & Pelisser, F. (2021). Use of calcined water treatment plant sludge for sustainable cementitious composites production. Journal of Cleaner Production, 327, 129484. https://doi.org/10.1016/j.jclepro.2021.129484

Singh, R. P., Vanapalli, K. R., Cheela, V. R. S., Peddireddy, S. R., Sharma, H. B., & Mohanty, B. (2023). Fly ash, GGBS, and silica fume based geopolymer concrete with recycled aggregates: Properties and environmental impacts. Construction and Building Materials, 378, 131168. https://doi.org/10.1016/j.conbuildmat.2023.131168

Superintendencia de Servicios Públicos Domiciliarios. (2023). Informe sectorial de los servicios públicos domiciliarios de acueducto y alcantarillado—Vigencia 2022 (p. 64). https://www.superservicios.gov.co/sites/default/files/inline-files/Informe-Sectorial-de-los-Servicios-Publicos-Domiciliarios-de-Acueducto-y-Alcantarillado-Vigencia-2022.pdf

Świerczek, L., Cieślik, B. M., & Konieczka, P. (2018). The potential of raw sewage sludge in construction industry – A review. Journal of Cleaner Production, 200, 342–356. https://doi.org/10.1016/j.jclepro.2018.07.188

Torres-Lozada, P., Arango-Vallejo, L. A., & Torres-López, W. A. (2022). Estimación de la producción de lodos en plantas convencionales de tratamiento de agua potable mediante modelos de predicción. Revista UIS Ingenierías, 21(4), Article 4. https://doi.org/10.18273/revuin.v21n4-2022008
Vouk, D., Nakic, D., Stirmer, N., & Cheeseman, C. R. (2017). Use of sewage of sludge ash in cementitious materials. Review on Advanced Materials Science, 49(2), 158–170.
Yang, K.-H., Jung, Y.-B., Cho, M.-S., & Tae, S.-H. (2015). Effect of supplementary cementitious materials on reduction of CO2 emissions from concrete. Journal of Cleaner Production, 103, 774–783. https://doi.org/10.1016/j.jclepro.2014.03.018
Yang, K.-H., Song, J.-K., & Song, K.-I. (2013). Assessment of CO2 reduction of alkali-activated concrete. Journal of Cleaner Production, 39, 265–272. https://doi.org/10.1016/j.jclepro.2012.08.001