

Development of a Prototype for Cement Bag Recycling: From Solid Waste to an Alkali-Activated Binder

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Desenvolvimento de protótipo para reciclagem de embalagens de cimento: do resíduo sólido ao aglomerante álcali-ativado

RESUMO

Objetivo – Desenvolver e apresentar um protótipo para o processamento de sacos de cimento contaminados, por meio de tratamento alcalino com solução de NaOH, visando ao seu reuso como material de construção.

Metodologia – Adotou-se uma abordagem experimental, envolvendo montagem e observação do protótipo e o tratamento alcalino do resíduo, obtenção de uma fração sólida e o reaproveitamento da solução residual de NaOH na produção de um aglomerante álcali-ativado, combinado com sílica ativa e metacaulim.

Originalidade/relevância – Sacos de cimento contaminados representam um resíduo sólido abundante nas cidades, com alternativas limitadas de reaproveitamento. O estudo aborda essa lacuna ao propor uma estratégia integrada de valorização das frações sólida e líquida.

Resultados – O protótipo processou cerca de 30 sacos de cimento com 4 L de solução de NaOH. O material sólido obtido apresentou baixa granulometria e potencial de aplicação na construção civil. A solução residual de NaOH foi reutilizada na produção de um aglomerante álcali-ativado, formando um sistema semelhante ao gel N-A-S-H, com razão molar (SiO_2/NaOH) de 6,41. O material apresentou tempo de início de pega de 51 minutos, fim de pega de 10 horas e resistência à compressão de até 1,46 MPa aos 60 dias.

Contribuições teóricas/metodológicas – O estudo demonstra a viabilidade técnica do reaproveitamento integrado dos resíduos sólido e líquido por meio de processamento alcalino.

Contribuições sociais e ambientais – Os resultados indicam potencial para mitigar o descarte de sacos de cimento e do consumo de cimento Portland, assim como pode ser uma contribuição para estratégias de economia circular na construção civil, promovendo uma gestão mais sustentável de resíduos.

PALAVRAS-CHAVE: Aglomerante. Economia circular. Sacos de cimento.

Development of a prototype for recycling cement packaging: from solid waste to alkali-activated binder

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ABSTRACT

Objective – To develop and present a prototype for the processing of contaminated cement bags through alkaline treatment with NaOH solution, aiming at their reuse as a construction material.

Methodology – An experimental approach was adopted, involving the assembly and monitoring of the prototype and the alkaline treatment of the waste, the recovery of a solid fraction, and the reuse of the residual NaOH solution in the production of an alkali-activated binder combined with silica fume and metakaolin.

Originality/Relevance – Contaminated cement bags represent an abundant solid waste in cities, with limited reuse alternatives. This study addresses this gap by proposing an integrated strategy for the valorisation of both solid and liquid fractions.

Results – The prototype processed approximately 30 cement bags using 4 L of NaOH solution. The recovered solid material exhibited fine particle size and potential for application in construction materials. The residual NaOH solution was reused in the production of an alkali-activated binder, forming a system similar to N-A-S-H gel, with a molar ratio (SiO_2/NaOH) of 6.41. The material showed an initial setting time of 51 minutes, a final setting time of 10 hours, and compressive strength of up to 1.46 MPa at 60 days.

Theoretical/Methodological Contributions – The study demonstrates the technical feasibility of integrated reuse of solid and liquid waste streams through alkaline processing.

Social and Environmental Contributions – The results indicate potential for reducing the disposal of cement bags and the consumption of Portland cement, as well as contributing to circular economy strategies in the construction sector by promoting more sustainable waste management practices.

KEYWORDS: Binder. Circular economy. Cement bags.

Desarrollo de un prototipo para el reciclaje de envases de cemento: del residuo sólido al aglomerante álcali-activado

RESUMEN

Objetivo – Desarrollar y presentar un prototipo para el procesamiento de sacos de cemento contaminados mediante tratamiento alcalino con solución de NaOH, con el objetivo de su reutilización como material de construcción.

Metodología – Se adoptó un enfoque experimental, que incluyó el montaje y seguimiento del prototipo y el tratamiento alcalino del residuo, la obtención de una fracción sólida y la reutilización de la solución residual de NaOH en la producción de un aglomerante álcali-activado combinado con sílice activa y metacaolín.

Originalidad/Relevancia – Los sacos de cemento contaminados representan un residuo sólido abundante en las ciudades, con alternativas limitadas de reutilización. El estudio aborda esta brecha al proponer una estrategia integrada de valorización de las fracciones sólida y líquida.

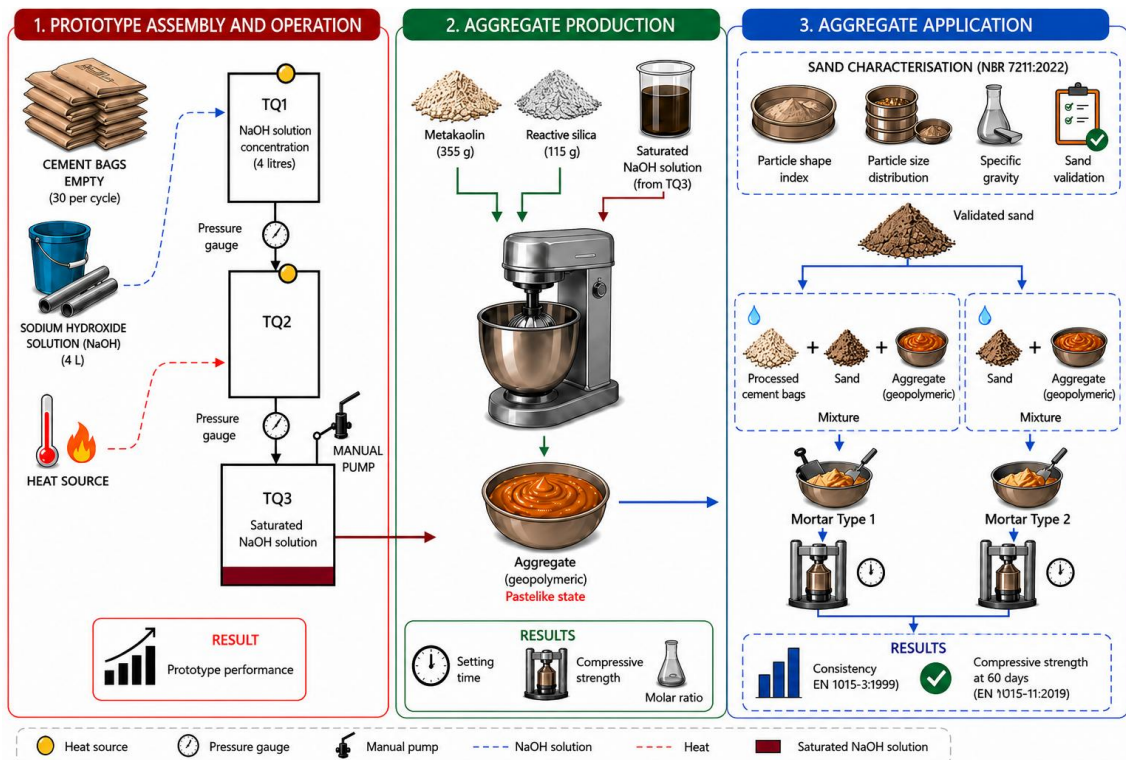
Resultados – El prototipo procesó aproximadamente 30 sacos de cemento utilizando 4 L de solución de NaOH. El material sólido recuperado presentó granulometría fina y potencial de aplicación en materiales de construcción. La solución residual de NaOH se reutilizó en la producción de un aglomerante álcali-activado, formando un sistema similar al gel N-A-S-H, con una relación molar (SiO_2/NaOH) de 6,41. El material presentó un tiempo de inicio de fraguado de 51 minutos, un tiempo final de fraguado de 10 horas y resistencia a la compresión de hasta 1,46 MPa a los 60 días.

Contribuciones teóricas/metodológicas – El estudio demuestra la viabilidad técnica de la reutilización integrada de las fracciones sólida y líquida mediante procesamiento alcalino.

Contribuciones sociales y ambientales – Los resultados indican potencial para reducir la disposición de sacos de cemento y el consumo de cemento Portland, además de contribuir a estrategias de economía circular en el sector de la construcción, promoviendo una gestión más sostenible de los residuos.

PALABRAS CLAVE: Aglomerante. Economía circular. Sacos de cemento.

GRAPHICAL ABSTRACT

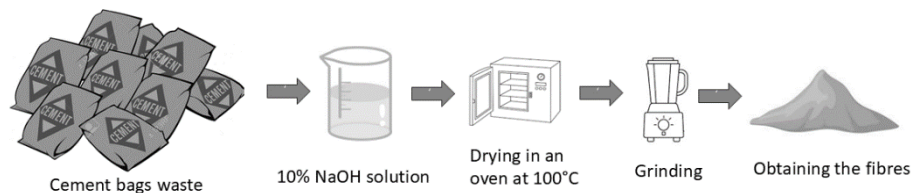


1 INTRODUCTION

Civil construction is a major generator of waste due to the use of materials from various sectors and with different chemical compositions. Among these waste products, contaminated cement sacks stand out; composed of multi-walled paper impregnated with cementitious particles, they are difficult to recycle using conventional methods and are generally sent to landfills or incineration. Concurrently, the sector is responsible for around 34% of global energy consumption and 37% of energy-related CO₂ emissions, with cement production alone accounting for approximately 7% of global emissions (UNEP, 2024). In Brazil, it is estimated that nearly 900 million cement sacks were discarded in 2024, highlighting limitations in reverse logistics and reuse systems (SNIC, 2025).

Although there are studies proposing the reuse of cement sacks in construction materials, incorporation rates remain low (Soares *et al.*, 2024a), indicating the need for technologies that expand reuse at the generating source itself, in line with the principles of the circular economy and climate neutrality targets. One of the methods investigated involves the alkaline treatment of kraft paper with sodium hydroxide (NaOH), as observed by Ji *et al.* (2018), Villar *et al.* (2025), and proposed by Soares *et al.* (2024b). In this process, the processed kraft paper sacks can be reused as fibres in thermoacoustic materials (Fig. 1), presenting low thermal conductivity (between 0.04 and 0.08 W/m·°C). However, this treatment generates a residual NaOH solution, the reuse of which is still poorly explored, potentially representing an opportunity for application in alternative cementitious systems as binders.

Figure 1 – Schematic diagram for the treatment of cement sacks with NaOH solution.



Source: Adapted from Soares *et al.* (2024b).

Alkali-activated binders (AABs), also known as geopolymers, are obtained from the reaction between aluminosilicate precursors and alkaline solutions, forming gels with high mechanical strength and durability. These materials can achieve compressive strengths exceeding 40–60 MPa, depending on the precursor and curing conditions (Provis & van Deventer, 2014). Furthermore, they exhibit better performance in aggressive environments compared to Portland cement (Bernal, 2016; Scrivener *et al.*, 2018), as well as a potential reduction in CO₂ emissions of between 9% and 90%, depending on the formulation and the origin of the materials (Geraldo *et al.*, 2026). In this context, the transition to a low-carbon economy can generate environmental and economic benefits, in addition to boosting new productive sectors (Zhang *et al.*, 2024).

Marques and Benini (2026) discuss that the management of civil construction waste presents challenges for sustainability, highlighting the need for reuse and recovery strategies for these materials within the production cycle. In this scenario, this study proposes the development of a prototype for processing contaminated cement sacks using an alkaline NaOH

solution, utilizing an evolutionary approach in relation to the method proposed by Soares *et al.* (2024c).

2 OBJECTIVES

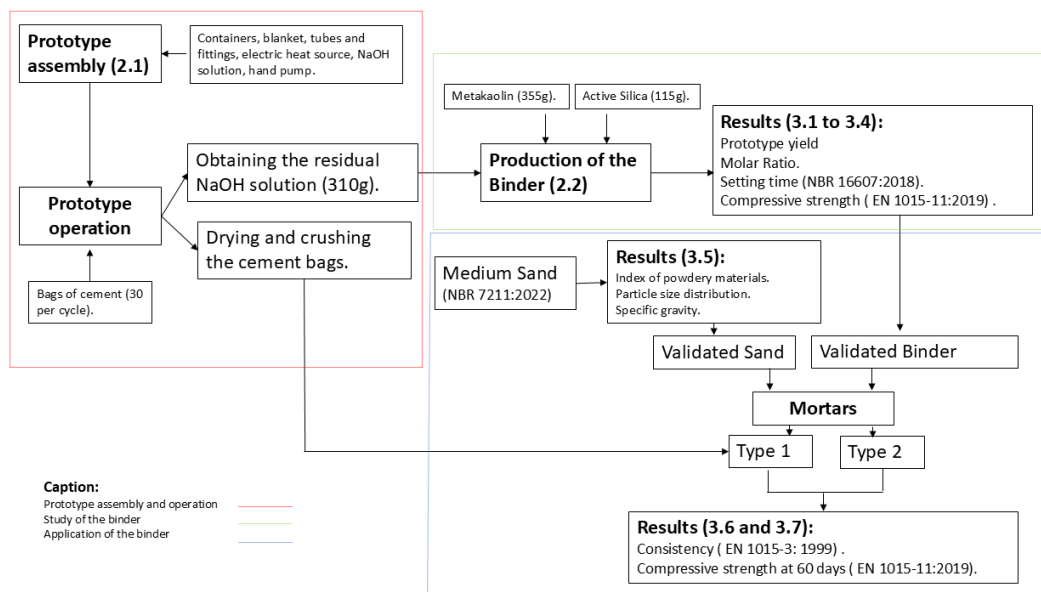
The objectives of this investigation are: (i) to disseminate the prototype for treating cement sacks; (ii) to obtain a solid material with potential for reuse; and (iii) to reuse the residual alkaline solution in the production of an alkali-activated binder based on silica fume and metakaolin, demonstrating a practical application.

It is worth noting that this investigation does not focus on obtaining materials with high mechanical strength, but rather on evaluating the technical feasibility of the proposed system, comparing the results obtained with the literature. The adopted strategy seeks to enable the incorporation of the binder into Portland cement-free mortars, expanding the reuse potential of the treated cement sacks.

3 METHODOLOGY

The methodology of this investigation was structured into three main phases. Phase 1 consisted of processing the cement sacks using the developed prototype, focusing on obtaining the solid and liquid by-products. Phase 2 comprised the production of the alkali-activated binder, whilst its application in mortar was implemented in Phase 3 (Fig. 2).

Figure 2 – Flowchart of the experimental programme.



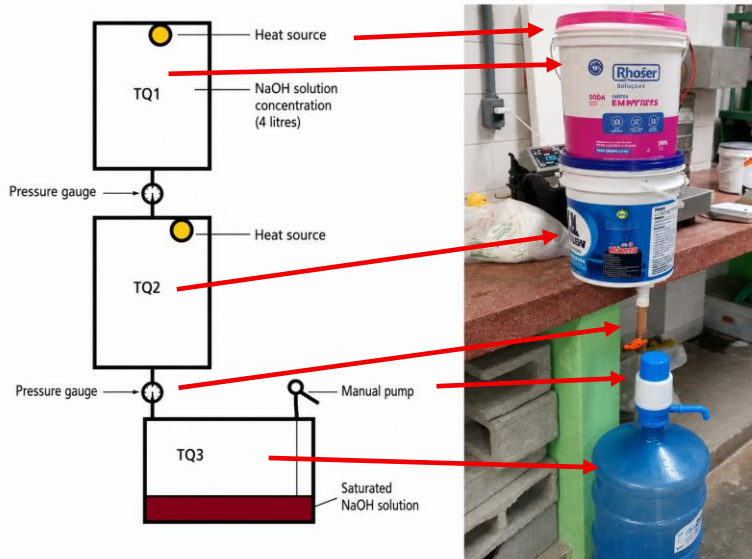
In Phase 1, the key focus is the treatment of the cement sacks using an alkaline NaOH solution within the developed prototype, resulting in the generation of two by-products: a solid residue, composed of fibrous material with a low particle size, and a residual alkaline solution. In Phase 2, the residual solution is reused as an activating agent in the synthesis of the binder, alongside metakaolin and silica fume, followed by Phase 3, which involves the application of the

material in mortar and its subsequent characterisation. This experimental setup demonstrates an integrated reuse approach, aligned with the principles of the circular economy.

3.1 Prototype assembly

The contaminated cement sacks were collected from local construction sites and screened to remove impurities. To facilitate processing, a prototype was assembled, in which 4 litres of a 10% concentration NaOH solution enter the first tank (TQ1). This same solution can be released through a valve into the second tank (TQ2) to perform a new cycle. The oven used by Soares et al. (2024b) was replaced by the heat source of a 60 W incandescent lamp (for approximately 6 hours), with the energy being conserved by the refractory linings of the tanks. Finally, the saturated NaOH solution can be released into the final container (TQ3), from which it can be extracted by pumping (Fig. 3).

Figure 3 – Designed, assembled and operational prototype.



Source: Authors (2026).

The efficiency of the prototype was evaluated by the volumetric waste processing capacity per cycle and by the amount of residual solution generated at the end of the process, according to Equation (1).

$$\eta = V_{sol} / N_{sacks} \quad (1)$$

where:

- η = system efficiency (L/sack);
- V_{sol} = initial volume of the solution (L);
- N_{sacks} = number of processed sacks.

After a full cycle, the volume of the residual activator was verified, which was subsequently used as a binder.

3.2 Production of the binder

3.2.1 Materials

The following materials were used in the production of the alkali-activated binder: residual sodium hydroxide (NaOH) solution (Bradoc®), employed as a chemical activating agent; commercial metakaolin (MK2), obtained through controlled calcination of kaolin and used as an aluminosilicate precursor; and silica fume (microsilica), a by-product of metallic silicon production, characterised by a high specific surface area and pozzolanic activity.

The previously processed Portland cement sack residue was used as the material of interest to evaluate reuse within the system. Standardised medium sand, in accordance with ABNT NBR 7211:2022, was used as the fine aggregate.

For the characterisation and preparation of the mixtures, the following were employed: a set of stainless steel test sieves, in accordance with ABNT NBR 17054:2022; a mechanical mortar mixer, in accordance with ABNT NBR 16541:2016; a Vicat apparatus for determining setting times, in accordance with ABNT NBR 16607:2018; cylindrical moulds for test specimens, in accordance with ABNT NBR 5738:2015; and a flow table, in accordance with EN 1015-3:1999.

Additionally, a domestic blender-type mixer (300 W, four blades, Moulinex brand) was used in the preliminary stage for shredding and disaggregating the cement sacks.

3.2.2 Methods

The alkali-activated binder (AAB) was prepared based on the procedure proposed by Silva et al. (2024), using 355 g of metakaolin, 115 g of silica fume (SiO₂) and 310 g of residual NaOH solution as the activating agent. The materials were homogenised in a mortar mixer for 60 seconds, resulting in a paste with a consistency suitable for moulding.

Therefore, three cylindrical test specimens with dimensions of 5×10 cm were moulded for material characterisation. The AAB was evaluated regarding the estimated molar ratio (SiO₂/NaOH), initial and final setting times, and compressive strength at 28 days.

Subsequently, the binder was used in the production of mortar by incorporating medium sand at a 1:1 ratio by mass (binder:sand). The resulting mortar was characterised regarding the properties of the fine aggregate, fresh-state consistency (via a flow table test) and compressive strength at 60 days.

Considering the absence of specific standards for alkali-activated binder systems, normative procedures applicable to conventional cementitious materials were adopted by analogy. Thus, the following references were used: ABNT NBR 16607:2018, for determining setting times; ABNT NBR NM 248, for the particle size analysis of aggregates; EN 1015-3:1999, for determining mortar consistency; and EN 1015-11:2019, for mechanical strength testing.

For comparative purposes, two types of mortar were produced. Type 1 mortar was composed of AAB and sand at a 1:1 ratio by mass, with a 5% replacement of the sand mass with material from the processed cement sacks, with an approximate particle size of 1 mm, based on

previous studies with conventional mortars. Type 2 mortar was composed exclusively of AAB and sand, in the same 1:1 ratio by mass.

4 RESULTS AND DISCUSSION

4.1 Prototype efficiency (η)

The tests conducted demonstrated that the prototype has the operational capacity to process approximately 30 cement sacks per full treatment cycle, utilizing an initial volume of 4 litres (L) of alkaline solution. Based on these values, an efficiency (η) of 0.084 L per processed cement sack was determined.

At the end of the cycle, the generation of approximately 1.5 L of residual NaOH solution was observed. Although this solution could be reintroduced into subsequent processing cycles, this study opted for its reuse in the production of the alkali-activated binder (AAB), aiming to evaluate the feasibility of integration between the system stages.

This result highlights the potential of the prototype for continuous waste processing, in addition to reinforcing the viability of the internal reuse of the alkaline solution, in line with circular economy strategies.

4.2. Estimated molar ratio (SiO_2/NaOH) of the AAB

The molar ratio (SiO_2/NaOH) was estimated based on the reactive silica content present in the precursors (metakaolin and silica fume) and the effective amount of NaOH available in the 10% alkaline solution. Considering that the residual solution exhibited turbidity, preventing its determination by titration, and that part of the NaOH could have been absorbed by the cement sacks during processing, the initial nominal concentration of the solution was adopted by approximation.

Initially, the mass of SiO_2 from the metakaolin was determined, considering a content of 55% reported by the supplier, and from the silica fume, adopting a typical SiO_2 content greater than 90%. Next, the number of moles of SiO_2 was calculated from its molar mass ($60.08 \text{ g}\cdot\text{mol}^{-1}$). For the NaOH, the effective mass present in the solution was estimated, and the conversion into moles was performed based on the molar mass of $40.00 \text{ g}\cdot\text{mol}^{-1}$. The molar ratio was obtained from the relationship between the total moles of SiO_2 and the available moles of NaOH, resulting in a value of 6.41 (Tab. 1).

Table 1 – Assumptions and results for the SiO_2/NaOH molar ratio.

Component	Mass (g)	Compound	(%)	Mass of the compound (g)	M ($\text{g}\cdot\text{mol}^{-1}$)	n (mol)
Metakaolin	355	SiO_2	55	195.25	60.08	3.25
Activated silica	115	SiO_2	90	103.5	60.08	1.72
Total SiO_2	—	—	—	—	—	4.97
Liquid waste	310	NaOH	10	31	40.00	0.78
Molar ratio $\text{SiO}_2 / \text{NaOH} = 6.41$						

Source: Authors (2026).

The estimated molar ratio exhibited a value higher than the range usually reported in the literature for metakaolin-activated systems (Provis & van Deventer, 2014; Bernal, 2016). Studies indicate that ratios between 2.0 and 3.5 tend to provide better initial mechanical performance and adequate workability. The high value obtained in this study is associated with the use of a residual NaOH solution with limited concentration, which reduced the availability of alkalis in the system.

Despite being above the range considered optimal, the material exhibited a pasty consistency suitable for moulding the test specimens, indicating that, even under conditions of low relative alkalinity, it was possible to promote the formation of a reactive system. However, this condition may have directly influenced the mechanical development of the material, contributing to the low strength values observed. These results reinforce the importance of controlling the molar ratio in alkali-activated systems, especially when using residual solutions as activators.

4.3 Setting time

The produced alkali-activated binder exhibited an initial setting time of 51 minutes and a final setting time of 10 hours. The initial time falls within the range usually reported for metakaolin-based systems activated with sodium hydroxide, which typically varies between 30 and 90 minutes, depending on the alkaline concentration, temperature and Si/Al ratio of the system.

The observed final setting time (10 hours) may be associated with the high molar ratio ($\text{SiO}_2/\text{NaOH} = 6.41$), which implies a lower relative availability of OH^- ions to promote the dissolution of the aluminosilicate precursor. This condition tends to delay the formation of the three-dimensional N-A-S-H gel network, prolonging the development of structural rigidity. Similar behaviours, characterised by higher setting times in systems with lower alkaline content, were reported by Provis (2014) and Provis & van Deventer (2014), highlighting the sensitivity of these materials to activator dosage.

Thus, the results indicate hardening kinetics compatible with systems activated by low-concentration alkaline solutions, presenting an initial time suitable for moulding and a final time coherent with the progressive structuring of the aluminosilicate matrix.

4.4 Compressive strength of the AAB

The considered molar ratio proved sufficient to promote the alkaline activation reaction, albeit with moderate mechanical development, resulting in a mean compressive strength of 1.81 MPa at 28 days (Tab. 2).

Table 2 – Compressive strength results of the binder.

Sample	Compressive strength (MPa)	Compressive strength (MPa)	Standard deviation
1	1.85		
2	2.19	1.81	0.39
3	1.41		

Source: Authors (2026).

The results demonstrate the preliminary technical feasibility of reusing the residual alkaline solution within the binder system itself, contributing to the reduction of effluent disposal and extending the life cycle of raw materials, in line with the principles of the circular economy applied to civil construction. The observed standard deviation (0.39 MPa) indicates a moderate dispersion of the results around the mean.

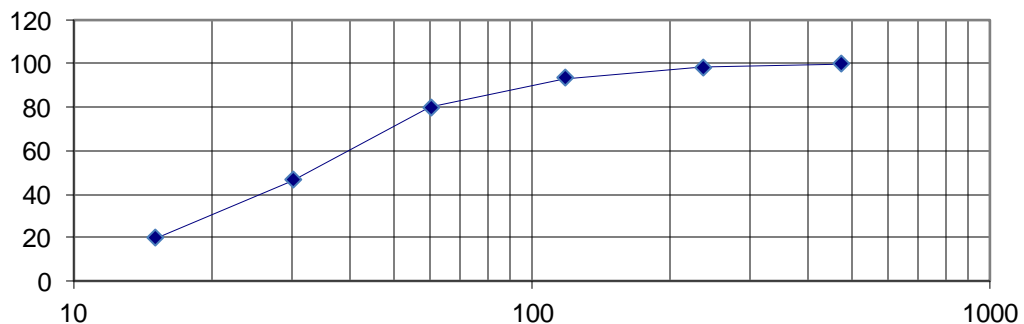
The low mechanical strength can be attributed to the limited alkalinity of the residual NaOH solution, with an estimated concentration of 10%, which may have restricted the dissolution of the aluminosilicate precursors and, consequently, the formation of a denser matrix. This condition is associated with the partial formation of the N-A-S-H gel, resulting in a less compact microstructure, as reported for systems activated with low alkaline concentrations (Provis & van Deventer, 2014; Bernal, 2016).

Despite the reduced mechanical performance, the values obtained are compatible with non-structural applications, such as partition elements, lightweight artefacts and levelling layers, as observed in studies with low-strength alkali-activated binders (Bernal, 2016). Therefore, the binder was considered technically viable for application in mortars, allowing the continuation of the experimental investigation.

4.5 Characterisation of the sand

The particle size analysis of the sand showed a continuous distribution, compatible with a medium-graded fine aggregate, without sharp discontinuities in the curve, which indicates adequate packing capacity and cohesion potential in the mixture. Figure 3 presents the particle size distribution curve of the sand used, highlighting the continuous distribution of particles across the analysed size fractions.

Figure 3 – Particle size distribution curve of the sand.



Source: Authors (2026).

The fines content exhibited values of 3.04% and 3.43% for samples 1 and 2, respectively, falling within the limits recommended by ABNT NBR 7211:2022 for aggregates used in the

production of mortars and concretes. These results indicate a low content of undesirable fine particles (passing through the 0.075 mm sieve), which tends to reduce water demand and enhance the adhesion between the paste and the aggregate.

The determined particle density (2.58 kg/dm^3) is within the typical range for natural quartz aggregates, corroborating the suitability of the material for application in cementitious matrices and alkali-activated systems. Overall, the characteristics obtained indicate that the aggregate used presents favourable conditions for the development of mortars with adequate volumetric stability and mechanical performance in non-structural applications.

This behaviour is consistent with studies that highlight the influence of particle size distribution and fines content on the workability and mechanical performance of mortars, especially in cementitious and alkali-activated systems, where the interaction between matrix and aggregate is decisive for microstructure formation (Scrivener *et al.*, 2018).

4.6 Consistence of the mortar

The consistence results of the mortar presented a flow value varying between 140 mm (Type 1) and 164 mm (Type 2), determined using a flow table in accordance with EN 1015-3:1999. This range characterises a medium consistence behaviour, indicating an adequate capacity for deformation under the standardised energy of the test.

The lower flow value (140 mm) is associated with a more cohesive and potentially more stable mixture regarding bleeding and segregation. Conversely, the higher flow (164 mm) indicates greater paste mobility, possibly related to the absence of cellulosic material in the Type 2 mortar, which may have reduced water absorption and increased the fluidity of the system. Additionally, the presence of fine particles, such as metakaolin and silica fume, may have contributed to the dispersion of the matrix and influenced the rheological behaviour of the mixture.

Overall, the results indicate workability compatible with manually moulded and compacted applications, without visual signs of segregation, demonstrating a balance between matrix fluidity and cohesion. This behaviour is consistent with studies that highlight the influence of the fine fraction and water retention on the consistence of mortars, especially in cementitious and alkali-activated systems (Scrivener *et al.*, 2018).

4.7 Compressive strength of the mortar at 60 days

The fresh bulk density varied between 1.06 g/cm^3 (Type 1) and 1.67 g/cm^3 (Type 2), demonstrating the significant influence of incorporating the cellulosic material from processed cement bags. Lower density values indicate greater initial porosity and higher void retention, whereas higher values suggest better granular packing and a lower volume of entrapped air.

A correlation trend is observed between higher fresh densities and greater mechanical strengths, indicating that mixtures with better compaction and lower void content result in more cohesive and stronger matrices. This relationship directly reflected on the mechanical performance at 60 days, with compressive strength varying between 0.81 MPa (Type 1) and 1.46 MPa (Type 2) (Tab. 3).

Table 3 – Compressive strength results of the mortars.

Type	Sample	Compressive strength (MPa)	Average (MPa)	Standard deviation
1	1	0.76		
1	2	0.84	0.81	0.04
1	3	0.83		
2	1	1.54		
2	2	1.29	1.46	0.14
2	3	1.54		

Source: Authors (2026).

The results indicate that the incorporation of waste from cement bags, at a proportion of 5%, promoted a reduction in compressive strength, possibly due to increased porosity and lower matrix densification. This behaviour is consistent with studies indicating that the introduction of fibrous or low-stiffness materials can compromise mechanical performance, while simultaneously contributing to other properties, such as density reduction and improved thermal performance (Scrivener *et al.*, 2018).

Despite the observed reduction, the values obtained are compatible with non-structural applications, such as partition elements, lightweight infills and components with a thermal function, especially considering the alternative nature of the precursors and the alkaline solution employed.

Therefore, it is recommended that future studies evaluate incorporation proportions of the waste below 5%, aiming to optimise the balance between mechanical performance and functional benefits, such as lightweighting and thermal insulation. These results demonstrate the application potential of the proposed system in materials with low structural requirements, reinforcing the feasibility of the integrated reuse of waste within the context of the circular economy.

4.8 Final considerations on the study

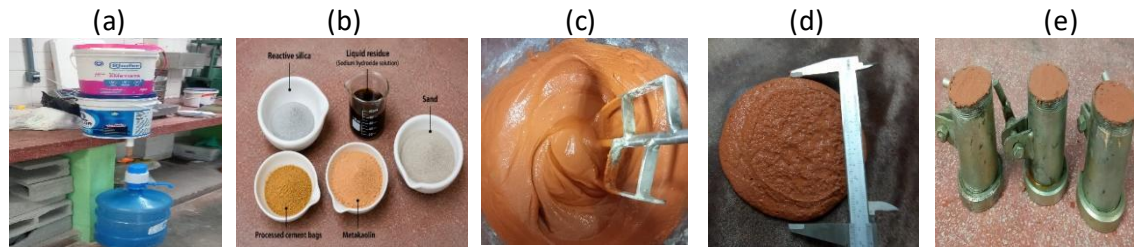
The results obtained demonstrated the feasibility of the integrated reuse of waste generated in the treatment process of cement bags, encompassing both the liquid and solid fractions. A total consumption of the alkaline solution was observed throughout the system, with a yield of 0.084 L per processed cement bag, alongside an energy consumption of approximately 0.36 kWh per cycle, corresponding to an efficiency of 0.012 kWh per bag. It is worth noting that this consumption can be associated with renewable energy sources, enhancing the environmental potential of the proposal.

The proposed method contributes to mitigating the impacts associated with the inadequate disposal of Portland cement bags, aligning with sustainability and circular economy strategies, in accordance with guidelines highlighted by international bodies (UNEP, 2024). Furthermore, the results reinforce the feasibility of the cement bag treatment previously investigated by Soares *et al.* (2024b), expanding its application through the incorporation of the liquid waste into the production of alkali-activated binders.

From a technical standpoint, the developed prototype, as well as the obtained materials—binder and mortar—presented operational conditions compatible with controllable

and potentially scalable processes, indicating feasibility for application within production contexts. Figure 4 illustrates the proposed system and its application stages, whilst Table 4 presents a comparison of the results obtained with reference studies.

Figure 4 – Prototype (a), mortar components (b), mixing (c) and technological control (d,e).



Source: Authors (2026).

Table 4 – Comparison of the present study with reference results.

Author	Precursor System	/ Activator	Molar ratio	Compressive strength	Age (days)
This study	Metakaolin + active silica	NaOH (~10%)	6.41	1.81 MPa / 1.46 MPa	28–60
Al- Azzawi <i>et al.</i> (2022)	Metakaolin	NaOH (low molarity)	~3.2	2.5 – 4.8 MPa	28
Bernal (2016)	Metakaolin	diluted NaOH	>4	1–10 MPa	28
Zhang <i>et al.</i> (2023)	Metakaolin	Carbonate-based activator	2.5 – 3.0	12 – 18 MPa	28
Provis (2014)	Metakaolin	NaOH	~3–4	5–25 MPa	28
Provis & van Deventer (2014)	Metakaolin	NaOH + silicate	2–4	20–50 MPa	28
Bernal (2016)	Metakaolin / slag	NaOH + silicate	2–3.5	30–60 MPa	28
Scrivener <i>et al.</i> (2018)	Cementitious systems	Miscellaneous	—	10–80 MPa	28

Source: Adapted from Provis & van Deventer (2014), Provis (2014), Bernal (2016), Scrivener *et al.* (2018), Al-Azzawi *et al.* (2022) and Zhang *et al.* (2023).

Comparison with the literature highlights that, although the mechanical strength values are lower than those of high-performance conventional systems, the results obtained fall within the range reported for systems activated with low alkaline concentrations, reinforcing the coherence of the experimental data and the consistency of the adopted approach.

Despite the observed advancements, the development of technologies associated with low-carbon systems still faces challenges, particularly regarding performance optimisation and large-scale viability (Lichtenberger *et al.*, 2022). In this regard, future studies should seek to improve activation conditions, adjust molar ratios, and evaluate new applications, including the *in loco* use of the developed binder.

5. CONCLUSION

The study demonstrated the technical feasibility of developing a prototype for processing contaminated cement bags, with an emphasis on the integrated reuse of the

generated waste. The proposed system enabled the attainment of a fine-grained solid material with reuse potential, as well as the recycling of the residual alkaline solution in the production of an alkali-activated binder.

The results further indicated a potential reduction in Portland cement consumption for non-structural applications, contributing to circular economy strategies within civil engineering. Despite the observed mechanical limitations, with a compressive strength of up to 1.46 MPa in the mortar, the material presented a performance compatible with low-structural-requirement applications.

As future perspectives, the optimisation of formulation parameters is recommended, especially the molar ratio and solids content, aiming to enhance mechanical performance. Additionally, it is suggested to conduct complementary tests, such as flexural strength, modulus of elasticity and capillary water absorption, for a more comprehensive characterisation of the material.

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DECLARATIONS

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DECLARATION OF COMPETING INTERESTS

We, Ricardo Soares, Rosana Fialho, Jardel Gonçalves, Sheyla Karolina and Ronny Souza, hereby declare that the manuscript entitled "**Development of a Prototype for Cement Bag Recycling: From Solid Waste to an Alkali-Activated Binder**":

1. **Financial Ties:** Has no financial ties or funding sources that could influence the results or interpretation of this work.
2. **Professional Relationships:** Has no professional relationships that could impact the analysis, interpretation or presentation of the results.
3. **Personal Conflicts:** Has no personal conflicts of interest related to the content of the manuscript."