

Article

Potential Use of Brewer's Spent Grain By-Product as a Component for Sustainable Thermal Mortars

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Abstract

Buildings represent approximately 40% of the total energy consumption. Net-zero energy buildings (NZEBS) have lower energy demands than conventional buildings due to improved thermal insulation combined with other passive design strategies. Thermal mortars, used in insulating plasters, help improve buildings' energy efficiency in a cost-effective manner, with minimal added thickness, even on irregular surfaces. Brewer's spent grain (BSG) accounts for 85% of the total by-products of the brewing industry. It is a cellulosic wood material, with a composition rich in protein (20%) and fiber (70%). Considering these properties, it has potential for use as a natural aggregate in mortars and as a sustainable material for buildings aligned with circular economy principles. This work aims to characterize BSG as a natural by-product for use in thermal mortars and identify different incorporation percentages. First, BSG was characterized in terms of its water content, particle size and volume mass. Then, mortars with BSG and fine sand, with different water contents, were produced and compared to a reference mortar and two commercially available thermal mortars. The performance of the mixtures was evaluated in terms of water absorption, mechanical behavior (namely, compressive and flexural strength) and thermal behavior. BSG mortars with a 0.25 w/c ratio presented a water absorption coefficient similar to that of the reference mortar. Overall, BSG mortars presented a mechanical strength profile similar to that of conventional thermal mortars. In the thermal test, the best BSG mortar (BSG75-w/c-0.25) achieved a stationary temperature difference between surfaces that was 8% lower than that of a commercial thermal mortar and 110% higher than that of the reference mortar. In sum, the best BSG mortars had a lower w/c ratio.

Keywords: circular economy; sustainable materials; by-product; thermal mortar; brewer's spent grain (BSG)

1. Introduction

More than 20% of the global emissions result from the energy demand and emissions of the building and construction sector. The United Nations has been issuing recommendations and



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monitoring progress toward the shift to zero-emission, energy-efficient and resilient buildings by 2050 [1]. The construction industry has several negative impacts on the environment, due to high demand for natural resources and increasing waste generation.

Increasing buildings energy efficiency is fundamental to addressing the risks and challenges posed by climate change [2]. The European Commission has been focusing on improving buildings energy efficiency through the directives 2009/72/EC, 2009/73/EC and the Energy Efficiency Directive 2018/2002.

Net-zero energy buildings (NZEBS) are designed to produce as much energy as they consume, combining high energy efficiency in buildings with on-site renewable energy production [3]. These buildings generally have lower energy demands due to improved thermal insulation combined with other passive design strategies [4]. The goal of NZEBs is the shift toward a more sustainable and resilient built environment, reducing greenhouse gas emissions and operational costs [5].

NZEBs and circular economy principles promote resource efficiency. While the goal of NZEBs is to balance energy consumption with renewable energy generation, circular economy promotes closed-loop systems that minimize waste and maximize material reuse [6]. Integrating circular principles into NZEBs involves careful material selection and life cycle thinking, including renewable, recyclable and low-impact resources for materials production. Biobased mortars, composed of natural materials or agricultural residues, exemplify this synergy, offering reduced embodied carbon, improved indoor air quality and compatibility with circular design due to their biodegradability and low environmental footprint [7]. Using such materials in NZEBs not only supports energy goals but also enhances the buildings' overall sustainability by aligning construction practices with regenerative and restorative economic models.

The use of passive design measures, such as the application of thermal insulation on buildings envelope, plays a fundamental role in improving the energy efficiency of buildings. Material selection must then contribute to the circular economy, aiming to minimize resource depletion and waste production.

Brewer's spent grain (BSG) is a by-product of the brewing industry obtained during the wort filtration stage. The filtered wort, in turn, is later used in fermentation to produce the final beer [8,9]. BSG is the residual component that is retained in industrial filters. BSG represents about 85% of brewing wastes, with a generation of 20 kg of wet BSG for each hectoliter of beer. For every ton of BSG landfilled, an estimated 513 kg of CO₂ equivalent is released [10]. BSG is initially wet but can be dried and processed in various ways for preservation. Nevertheless, BSG is a perishable product, which degrades quickly and loses its nutritional value. From a histological point of view, BSG contains some grains and the residual insoluble part of malted barley such as the husk, pericarp and aleurone; in terms of chemical composition, BSG is mainly composed of hemicellulose (30.60%), cellulose (21.42%), proteins (20.93%), lignin (11.41%), arabinoxylans (10.37%), starch (10.21%), lipids (8.52%) and small percentages of ash and β -glucans [11]. The porous structure of BSG provides good air retention properties, offering significant potential as an alternative to other sustainable materials with insulating properties used in construction, such as rice husk. Being a renewable and biodegradable material, BSG has advantages over traditional synthetic materials, promoting sustainability by reducing energy consumption and greenhouse gas emissions while reusing waste from a circular economy perspective [11,12].

In terms of annual draught production, an increase is expected in Europe, with an estimated value of 8.5 million tons [11]. Table 1 shows the availability of BSG in the Portuguese territory, compared to other materials, as well as the average water content in its composition (50 to 80%).

Table 1. Agro-industrial by-products of cellulosic, wood-based origin with great potential for valorization. Reprinted from Ref. [13].

By-Product	National Total (mg)	Water Content (%)
Brewer's spent grain (BSG)	97,536.2	50–80
Grape pomace	69,840.0	20
Carob pulp	40,000.0	10
Rice husk	34,535.7	13
Tomato by-product	30,768.9	70
Olive pomace	23,745.0	11
Nut peel	13,584.0	11
Grape stalks	9316.0	20
Wine dregs	8992.0	-
Grape seed	5400.0	10

Currently, BSG is mainly used as cattle feed [11] and is eventually discarded for composting. Recent research has demonstrated its potential use in the food industry, with some examples including fermented products [14] and its use as a source of bioactive compounds [15]. However, the BSG obtained during the brewing process showed a decrease of its nutritional properties over a short time period, thus proving to be a consistent option of repurposing a by-product as a material for the construction industry. Recent research demonstrated the potential of BSG to improve the thermal insulation of bricks [16], serve as fine aggregate in concrete [17], create insulation panels when combined with other bio-based materials [18] and be used as ash to partially replace cement in mortars production [19]. Finding ways to reuse and pretreat this material can benefit the brewing industry by reducing the costs associated with its waste, reducing its environmental impact and consequently ensuring a positive effect on the circular economy [12].

Natural aggregates such as expanded cork granules and expanded clay are commonly used to reduce the weight of concrete, screed and mortars [20–23] while improving their thermal and acoustic properties [24,25]. Recent research demonstrated the use of agro-industrial by-products in mortar production. The application of rice husk ash in cement mortars was tested by [26]. Ref. [27] also studied cement-based composites made with rice husk and tested them for use as acoustic barriers and thermal insulation materials. The effects of hydroxyethyl methyl cellulose, a product derived from cellulose, on calcium aluminate cement was tested by [28]. The study identified the effects of delayed hydration process and reduced compressive strength in calcium aluminate cement. The use of natural fibers in mortars has also been tested by [29], demonstrating the potential of alternative materials to improve thermal insulation and sustainability in construction. The study shows how plant fibers can significantly improve the thermal insulation of mortars, promoting sustainability in construction and demonstrating the viability of more environmentally friendly construction practices.

This study presents a laboratory investigation into the potential use of BSG in thermal mortars as a strategy to promote the valorization of this industrial by-product, thereby extending its life cycle through the application of circular economy principles. The novelty of this work lies in the analysis of the potential use of BSG as an aggregate in cementitious mortars and its comparison with thermal mortars available in the market, in which some mixtures showed promise.

2. Materials

For the preparation of mortars, a limestone Portland cement CEM II/B-L 32.5N was used as binder. This cement is composed of 65% to 79% Portland clinker, 21% to 35%

limestone and up to 5% other constituents. River sand with a granulometry between 0 and 4 mm was used as an aggregate for concrete, consisting mainly of 98.5% silica, 0.85% aluminum, 0.08% iron oxide, 0.04% sodium oxide, 0.02% potassium oxide, 0.01% calcium oxide and 0.01% magnesium oxide.

BSG was used as aggregate, replacing partially or entirely the amount of sand. The BSG used in the present study, as shown in Figure 1, was obtained in a pilot beer production unit located at Lusófona University in Lisbon. The BSG results were achieved by mashing 36% of Pilsen malt, 20% of light Munich malt and 44% of Vienna malt. The milled cereals were added to the mashing kettle with 35% water during the mashing process. The mixture was stirred for 30 min at 37 °C. After this stage, the temperature was raised to 62 °C for an additional 60 min. Then, the temperature was raised to 72 °C and kept constant for 20 min. Finally, the iodine test confirmed saccharification, and the temperature was raised to 80 °C. Stirring was maintained for 10 min during the enzyme inactivation phase. The mixture was transferred to the filtration stage and the solid phase—BSG was recovered from the process. BSG is composed of elongated grains of different sizes that tend to agglomerate when wet (Figure 1). Before adding the BSG to the cement mortars, wet and dry samples were analyzed to identify the best conditions for its use in this field. Furthermore, additional results characterizing BSGs, namely granulometry, water content and relative density, are presented in Section 4.1.



Figure 1. Wet BSG (a) and dry BSG (b).

The reference mixture included a 1:3 ratio, with Portland cement CEM II/B-L 32.5 N as binder, washed white sand for concrete as aggregate and a water–cement ratio (w/c) of 0.5. For the mortars with BSG only, the sand was entirely replaced by BSG and water-to-cement ratios of 0.25, 0.50 and 0.75. However, it was observed that excess water was present in the mixtures with a w/c ratio of 0.75. Moreover, in spite of being able to be tested for mechanical resistance, these samples partially disintegrated during their manipulation. Hence, after testing these mixtures, a second stage of this study included mixtures with two aggregates, including BSG (50% and 75%) and washed white sand (25% and 50%) and water-to-binder ratios of 0.25 and 0.50. All mixtures, including BSG, were prepared based on the standard EN 998-1 [30].

These second-stage mixtures were then compared to two thermal mortars available on the Portuguese market: one composed of hydraulic lime and cork granules, referred to as NHL–cork (with a granulometry between 0 and 3.5 mm), and another composed of white cement and expanded polystyrene granules, referred to as cement–PS (with a granulometry between 0 and 2 mm) (Table 2). The characterization of these mixtures in both the fresh state and after curing is presented in Sections 4.2 and 4.3, respectively.

Table 2. Mortar composition.

Sample	Volumetric Ratio	Binder	Aggregates		Water–Cement Ratio
		Cement	BSG	Fine Sand	
BSG100-w/c-0.25	1:3	1	3	-	0.25
BSG100-w/c-0.50	1:3	1	3	-	0.50
BSG100-w/c-0.75	1:3	1	3	-	0.75
BSG50-w/c-0.25	1:2:2	1	2	2	0.25
BSG50-w/c-0.50	1:2:2	1	2	2	0.50
BSG75-w/c-0.25	1:3:1	1	3	1	0.25
BSG75-w/c-0.50	1:3:1	1	3	1	0.50
Reference	1:3	1	-	3	0.50
NHL–cork	2000 g (pre-dosed mixture) + 960 mL of water, density: $200 \pm 50 \text{ kg/m}^3$				
Cement–PS	2500 g (pre-dosed mixture) + 500 mL of water, density: $700 \pm 50 \text{ kg/m}^3$				

3. Test Methodologies

First, the water content of the BSG was determined by adapting the EN 1097-5 standard [31]. For this purpose, dry and wet BSG samples were tested by determining their initial and final masses after drying in a ventilated oven at 60°C , until a constant mass was obtained. For the analysis of the wet BSG, two different samples were used, since the filtration and storage conditions used in the production unit can be variable.

The determination of the particle size of the BSG was carried out according to the standard NP EN 933-1 [32] used for the granulometry analysis of the aggregate, with the BSG having been previously dried in a ventilated oven until a constant mass was obtained.

The relative density of the BSG was determined based on the adaptation of the EN 1097-3 standard [33]. In this study, 4 samples were tested: dried BSG, placed in a ventilated oven for 24 h at 60°C ; air-dried BSG; wet BSG, obtained directly from the production unit; and saturated BSG, immersed in water for 2 h. The relative density of these samples was obtained by weighing the mass of 1 dm^3 of each material without compression. The relative density is given by the ratio between the mass of the substance and its volume, including voids.

To analyze the workability of mortars in the fresh state, their consistency was analyzed as indicated in the EN 1015-3 standard [34]. The spreading of fresh mortars containing BSG was measured using a ruler to record the initial and final diameter in two perpendicular directions. In this case, 3 BSG mortars with a 1:3 volumetric ratio and 0.25, 0.50 and 0.75 of water-to-cement ratios were analyzed.

The pH was also analyzed for the fresh mortars containing only BSG as aggregate and 0.25, 0.50 and 0.75 water-to-cement ratios and compared to the pH of the reference mortar. For these measurements, a Fisherbrand Accumet AB150 pH meter was used.

The water absorption coefficient due to capillary action in hardened mortar was tested based on the adaptation of the NP EN 1015-18 standard [35]. Three samples of $4 \times 4 \times 10 \text{ cm}$ of each mixture were prepared for this purpose and cured for 28 days. Prior to testing, the specimens were dried at 40°C in a ventilated oven until a constant mass was obtained. The different mortars were placed vertically in a tray, with water close to the bottom (about 5 mm above the bottom of the mortar) and weighed after 2 min, 5 min, 10 min, 15 min, 20 min, 30 min, 45 min, 1 h, 1 h and 30 min, 2 h, 4 h and 24 h.

The characteristics of the mortar samples with BSG, after curing, were compared with a reference mortar with a 1:3 volumetric ratio and a water-to-cement ratio of 0.5. In this study, the mechanical resistance of mortars was analyzed, and a methodology for the analysis of heat transmission was defined.

For the mechanical resistance testing, a Matest hydraulic press equipped with a Servotronic hydraulic servo controller was used. The compressive strength was determined according to the NP EN 1015-11 standard [36]. Three samples with $4 \times 4 \times 10$ cm of each BSG mortar mixture were tested for flexural resistance. After completing this test, both halves of the same sample were used in the compressive test. The reference mortar was compared to the BSG mortars containing different percentages. Table 2 presents the composition of each mixture for the production of prismatic specimens. The tests were carried out after 7, 14 and 28 days of curing without the use of a saturated chamber, since the BSG retains water for a long period of time in the mortar.

The flexural strength was determined according to the NP EN 1015-11 standard [36] for the different mortars and for the same curing days previously defined for the compression tests.

An experimental procedure was defined to evaluate the potential use of these mortar samples as thermal mortars. According to the simplified Fourier law, for plane parallel walls, under a constant temperature gradient ΔT , the heat transferred over time is given by

$$\frac{Q}{\Delta T} = -kS \frac{\Delta T}{\Delta x},$$

where Q is the amount of heat transferred over time Δt , k is the material's conductivity, S represents the surface through which the heat flows, ΔT is the temperature difference between the two faces of the sample, and Δx is the distance between faces (i.e., the thickness of the sample). Thermal resistance is defined as

$$R_T = \frac{1}{k} \frac{\Delta x}{S},$$

It is possible to relate the transference time Δt and the thermal resistance through

$$\Delta t = -R_T \frac{Q}{\Delta T}.$$

Hence, the greater the thermal resistance, the longer it takes to transfer the same amount of heat (under the same temperature difference between faces) from one face to the other of the sample. Based on this principle, an experimental procedure was devised, to infer the sample's thermal resistance.

In the test, a Guardian 3000 hotplate was used as a heat emission source, with programmable temperature and a set of 3 digital thermometers, with an external probe (accuracy of ± 1 °C). The 3 temperature probes were placed, respectively, on the surface of the heating plate, on the upper and lower sides of the sample (Figure 2). The surface temperature values on both sides of the sample, as well as on the surface of the plate, were continuously measured for 24 h.

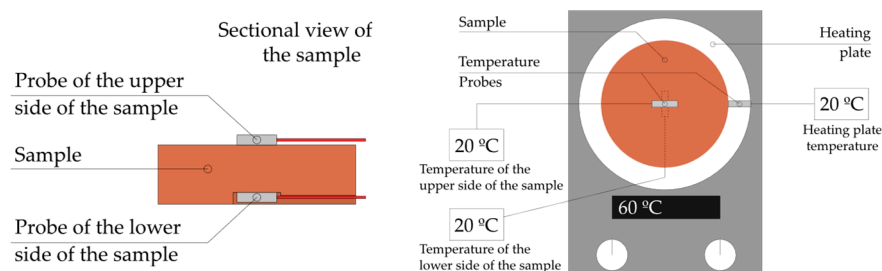


Figure 2. Experimental assembly with indication of the placement of samples and respective temperature probes.

This procedure aims to simulate heat transmission through building materials by measuring the temperature difference (ΔT) between the faces over time. Note that the ambient temperature is much lower than that of the surface of the hotplate. Hence, the surface temperature of the sample's face in contact with air (t_{sup}) will not reach the surface temperature of the face in contact with the hotplate (t_{inf}), due to thermal losses through convection and radiation. Therefore, an equilibrium stage is achieved, with constant temperatures for both faces, where $t_{sup} < t_{inf}$. This test was carried out to assess the performance of the materials as thermal mortars, since those with higher thermal resistance will present a higher ΔT at their equilibrium stage.

For this test, cylindrical specimens with approximately 10 cm in diameter and 3 cm of thickness were produced for each mortar under study and left to cure for 28 days. After curing, all samples were dried in a ventilated oven for 3 days at 60 °C until constant mass was obtained. A groove was opened with a drill in the underside of the specimens to accommodate one temperature sensor. Hence, one sensor was placed on top of the plate, at the center of the sample, and the other on top of the sample, also in its center. In addition, a third sensor was attached to the side of the heating plate (Figure 2). The thermal tests consisted of heating the underside of the specimen on the hotplate (set at 60 °C), while the upper side was exposed to room air for 100 min, with minute-by-minute temperature measurements taken by the sensors. The room air temperature was kept at 20 °C throughout the tests. This procedure made it possible to obtain the temperature differential (ΔT) between the bottom and top surfaces for each specimen, to infer its thermal behavior. For this test, besides the specimens with BSG, commercially available thermal mortars (NHL–cork and cement–PS) and a sample of XPS (expanded polystyrene) were also evaluated, to compare BSG samples with conventional insulation materials.

4. Results and Discussion

4.1. BSG Characterization

As shown in Table 3, the dry BSG has a water content of 2%, which is relatively low when compared to the wet BSG, whose water content varied between 37% and 53%.

Table 3. Water content of BSG samples.

BSG Analyzed	Water Content (%)
Dry BSG	1.98
Wet BSG—Test 1	37.44
Wet BSG—Test 2	53.14

It can thus be seen that the results of the wet BSG obtained are in accordance with the literature, since the water content of the brewer's spent grain varies between 40% and 80%. In this case, it is considered more advantageous to use wet BSG in the preparation of mortars, reducing the energy expenditure with the drying of the material while also avoiding the consumption of additional water for its hydration.

The particle size distribution of BSG was obtained through the sieving and separation of the dry BSG particles. Figure 3 shows the particle size distribution curve of the BSG. Most BSG particles were found in intervals between 1 to 4 mm with 20.5% of particles between 1 to 2 mm and 62.5% between 2 to 4 mm, characterizing it as a fine aggregate [21]. Given the particle size distribution of BSG, it can be considered suitable for use as an aggregate in mortars.

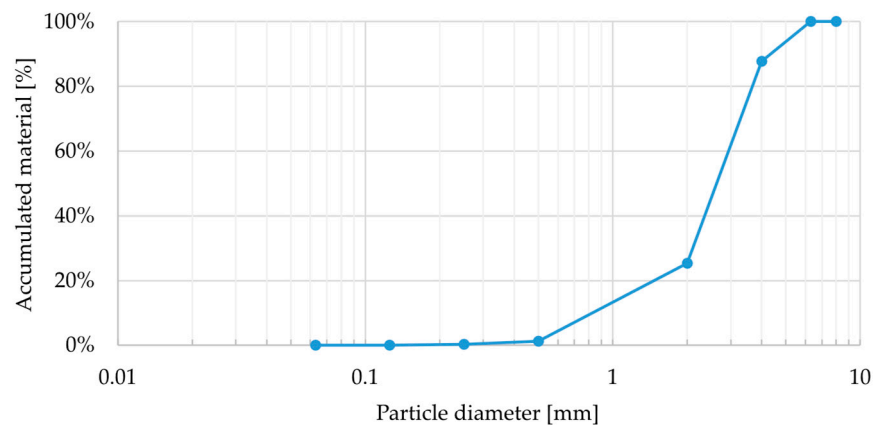


Figure 3. Granulometry curve of BSG.

The relative density of BSG was determined under four different conditions, as shown in Table 4. For this purpose, dried, wet and saturated samples were compared to identify if there would be significant differences in their relative density. The relative density of dried BSG samples is similarly low when compared to that of a very lightweight aggregate [21]. Similarly, the relative density of wet BSG is very close to that of saturated BSG. The difference in the volume mass between these two groups is due to the presence of water in the intra- and inter-particle voids of the BSG. Given that the densities of samples 3 and 4 are similar, it was decided to use the wet BSG supplied directly by the production unit, thus reducing the amount of water needed for mortar production.

Table 4. Relative density of BSG samples.

Type of BSG	Density (kg/m ³)
Dried BSG (60 °C for 24 h)	190.1
Air-dried BSG (room temperature)	180.7
Wet BSG (obtained from the production unit)	513.5
Saturated BSG (immersed in water for 2 h)	534.1

4.2. Characterization of Mortars in the Fresh State

The consistency of BSG mortars was measured according to the EN 1015-3 standard [34], and it was verified that the values obtained were quite low, as shown in Table 5.

Table 5. Spreading of the mortars with BSG obtained using different percentages of water.

Water-to-Cement Ratio (w/c)	Spreading (mm)
0.25	100
0.50	120
0.75	130

For the mortar with a 0.25 w/c ratio, a spread of 100 mm was obtained. The mortars with 0.50 and 0.75 w/c ration also showed low spreading values of 120 and 130 mm, respectively. The fact that the spreading values are low can be either a beneficial or a limiting factor, depending on its application on site.

The pH of all mortars is significantly high (Figure 4). As expected, the reference mortar obtained the highest pH value of 13.20, as cement has a pH close to 14. After the introduction of BSG, the pH of the mortars was slightly reduced. This reduction is related to BSG's acidic profile, with a measured pH value of 5.35, which is in accordance with the values cited in the literature [37,38]. The minimum pH measured was 11.96 for

the BSG100-w/c-0.75, whereas a pH of 12 was obtained for the samples with a lower water-to-cement ratio.

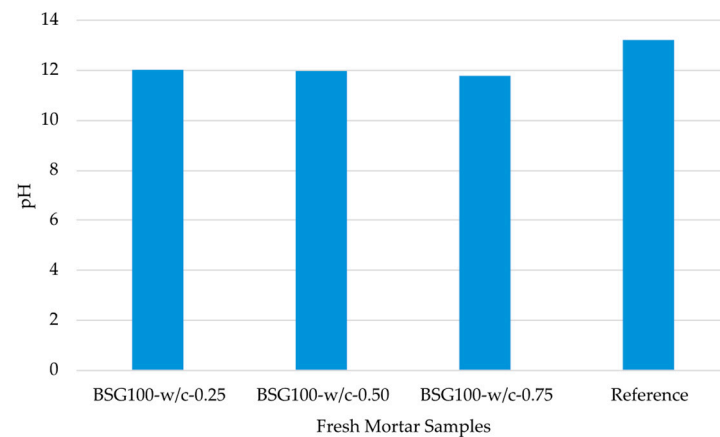


Figure 4. pH values of fresh mortar samples.

4.3. Characterization of Mortars After Curing

4.3.1. Water Absorption

The results showing the capillary water absorption of the different mortars over time can be observed in Figure 5. In addition, the water absorption coefficients were determined for all mortars (Table 6). The mixture BSG100-w/c-0.75 was excluded from this analysis due to the fact that it still contained an excessive amount of water after curing and disaggregated during its manipulation after the drying process.

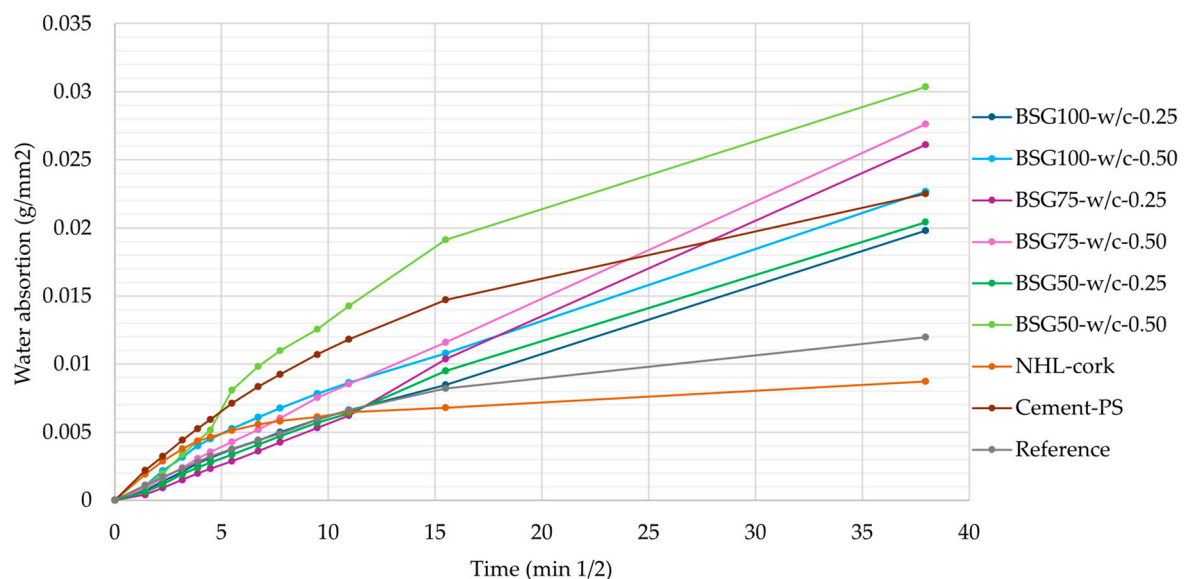


Figure 5. Water absorption by capillarity.

The NHL-cork mortar has the lowest capillary absorption coefficient, at $0.37 \text{ kg/m}^2 \cdot \text{min}^{0.5}$, followed by the reference samples, at $0.57 \text{ kg/m}^2 \cdot \text{min}^{0.5}$. These were also the mortars that stabilized water absorption sooner. Mortars with a water-to-cement ratio of 0.25 have a lower capillary absorption coefficient than the other samples containing BSG, suggesting that they are less porous. This result suggests that the specific combination of BSG and sand may create a denser and less permeable matrix, which brings the capillary absorption coefficient closer to that observed in the NHL-cork mortar. The reduction in capillary absorption may be indicative of better performance in terms of durability and

resistance to water penetration, which is desirable in construction applications. On the other hand, the BSG samples with a w/c ratio of 0.50 and cement-PS showed significantly higher capillary absorption compared to the other mortars. This result indicates that these mortars have a more porous structure, allowing greater penetration of water by capillarity. This characteristic can be disadvantageous in terms of durability and water resistance, since greater absorption can lead to degradation problems over time. Another important point observed was that only the NHL-cork mortar stabilized water absorption by capillarity after 4 h. The other mortars continued to absorb water after this period. This stabilization behavior of NHL-cork can be attributed to its composition and structure, which creates an effective barrier to the continuous penetration of water. Stabilizing absorption is a crucial factor for the longevity and durability of mortars, as it limits the amount of water that can penetrate and potentially damage the structure.

Table 6. Water absorption coefficient.

Samples	Water Absorption Coefficient (kg/m ² .min ^{0.5})
BSG100-w/c-0.25	0.77
BSG100-w/c-0.5	0.95
BSG50-w/c-0.25	0.60
BSG50-w/c-0.50	1.46
BSG75-w/c-0.25	0.60
BSG75-w/c-0.50	0.93
Reference	0.57
NHL-cork	0.37
Cement-PS	1.00

4.3.2. Mechanical Resistance

The evaluation of the flexural and compressive strength of the mortars was carried out after 7, 14 and 28 days of curing, allowing the analysis of their behavior until complete curing was achieved. Figures 6 and 7 show the results obtained for flexural strength and simple compression, respectively, as well as the standard deviation verified in the four specimens tested at each curing age. A maximum compressive strength test was conducted; however, the BSG mortars did not exhibit brittle failure. Rather, they displayed deformation, which allowed the test to continue without complete specimen failure. Both flexural and compressive strength tests showed that the mechanical resistance of the samples increased over time. From the results presented in Figures 6 and 7, it is possible to verify that the BSG specimens with a 0.25 w/c ratio showed greater mechanical resistance to both compression and flexure when compared to the results obtained for the BSG mortars with 0.50 and 0.75 w/c ratios. Note that, the properties of the reference mixture are known in the literature and are much higher than those of the analyzed samples (typically 10 to 25 MPa). Hence, these mixtures demonstrate a mechanical behavior that is more similar to that of thermal mortars, in line with the results presented by [39], who compared the mechanical performance of thermal mortars.

4.3.3. Thermal Analysis

A detailed analysis of the thermal difference between both faces of the mortar samples (ΔT), obtained over time using the procedure described in Section 3, is shown in Figure 8. The samples are heated from the bottom surface in contact with the hot plate, then the heat is conducted through the surface until it reaches the upper surface. This thermal difference tends to be a constant value after some time (threshold), which corresponds to the thermal equilibrium of the sample. Samples with greater thermal insulation potential present a

higher temperature difference between faces, showing slower heat transfer over time. The final value for this difference ΔT_f was calculated as the average value of ΔT for the last 20 min of the test (Table 7). The upper and lower limits for ΔT_f are given by the insulating reference XPS sample and the reference mortar sample, respectively.

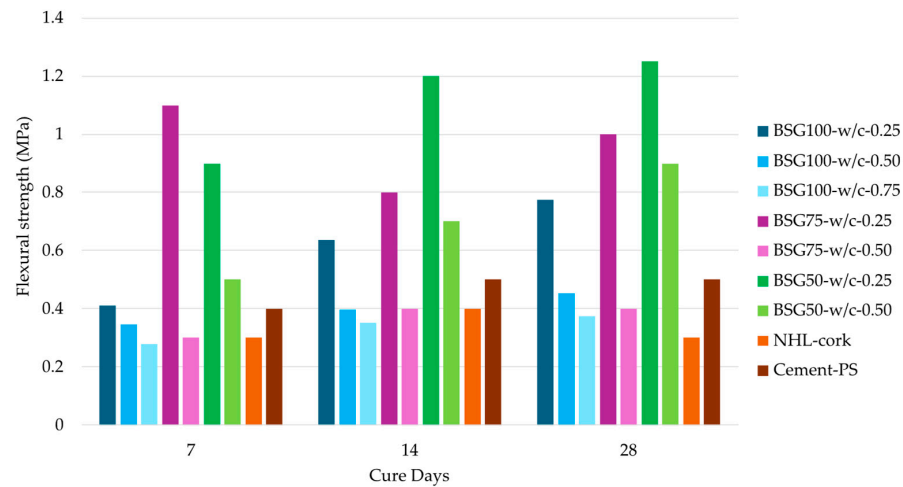


Figure 6. Determination of flexural strength.

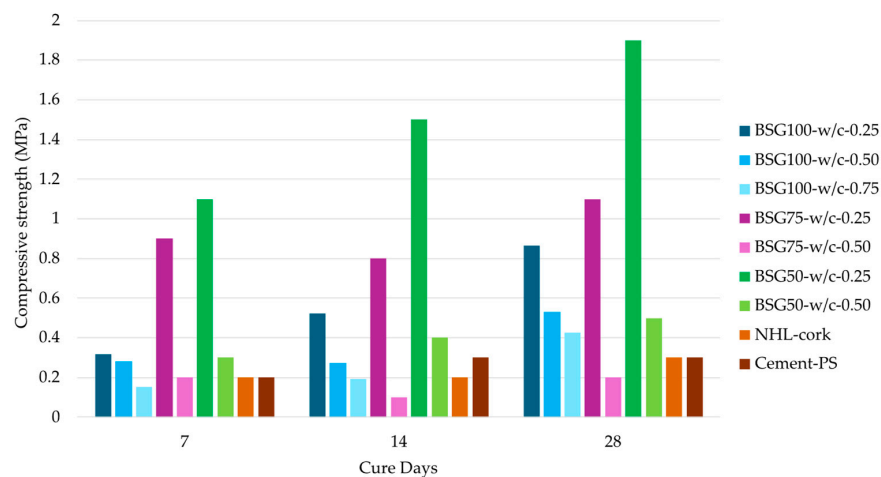


Figure 7. Determination of compressive strength.

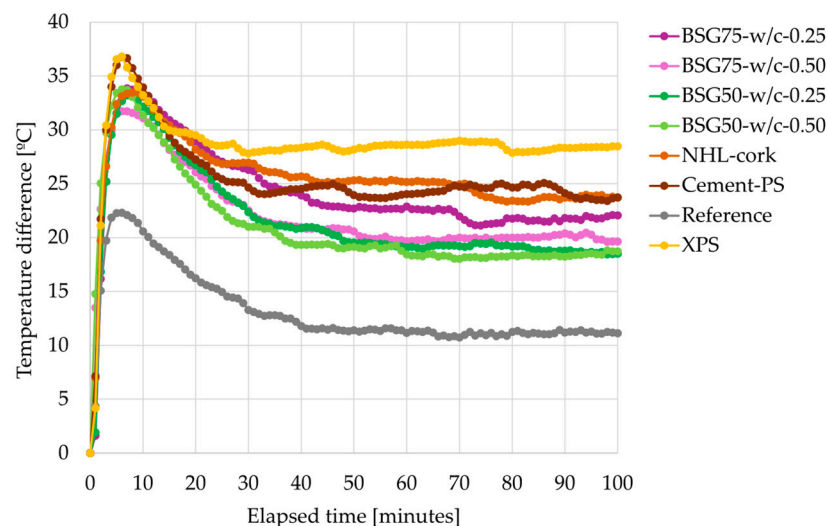


Figure 8. Temperature difference between the two faces of the sample over time.

Table 7. Final value of ΔT , calculated as the average value of the last 20 min of the test.

Samples	ΔT_f [°C]
XPS	28.25
Cement-PS	24.18
NHL-cork	23.69
BSG75-w/c-0.25	21.76
BSG75-w/c-0.50	20.05
BSG50-w/c-0.25	18.75
BSG50-w/c-0.50	18.40
Reference	11.18

The highest thermal difference was identified for cement-PS commercial mortar, followed by NHL-cork, both known as commercial thermal mortars. With regard to BSG mortars, it can be observed that BSG75-w/c-0.25 and BSG75-w/c-0.50 are the ones that performed best and, in fact, come quite close to the performance of commercial mortars, revealing that these mixtures may present good behavior when used as thermal mortars. Following these, are the BSG50-w/c-0.25 and BSG50-w/c-0.50 mortars, which indicate that a higher concentration of BSG in the mixture improves the thermal insulation potential due to its natural properties.

5. Conclusions

In this exploratory study, BSG, as an industrial by-product, showed its potential for use in thermal mortars for plastering. The results obtained herein are fundamental in establishing a basis for further optimization of a sustainable product that uses BSG as an aggregate. According to the water absorption results, the mortars containing brewers' spent grain showed lower initial water absorption, especially in the BSG mixtures with a w/c ratio of 0.25, suggesting a denser and less permeable matrix, with the BSG75-w/c-0.25 and BSG50-w/c-0.25 achieving $0.6 \text{ kg/m}^2 \cdot \text{min}^{0.5}$ for the water absorption coefficient. Similarly, this study indicates that mortars with added fine sand show lower absorption due to their denser structure. However, further research is needed to optimize the methodology and fully understand the long-term behavior of these mixtures.

Regarding the mechanical stress tests, the performance of the mixtures, led by BSG50-w/c-0.25, which achieved a flexural strength of 1.24 MPa and a compressive strength of 1.9 MPa, is comparable to that of typical thermal mortars, albeit lower than that of the reference mortar.

Regarding the thermal analysis, the tests carried out highlighted the competitive profile of BSG mortars in terms of thermal properties, showing a high thermal difference between faces when compared to the conventional reference mortar. Namely, the best sample, BSG75-w/c-0.25, achieved a stationary temperature difference between surfaces that was only 8% lower than that of the commercial thermal mortar and 110% higher than that of the reference mortar.

In future research, it is important to undertake a microstructural analysis of the mixtures, resorting to techniques such as SEM, XRD or FTIR, to explain the interaction between BSG particles and the cementitious matrix, in order to clarify the bonding, porosity and hydration characteristics. Such an analysis will allow a deeper interpretation of the water retention and hydration kinetics properties, or failure mechanisms, of the BSG mixtures. An extended analysis of the pH for each tested mixture must also be undertaken. Regarding water absorption, the experimental period of contact between the specimens and the water will also be extended. This extension will make it possible to determine the exact moment when the absorption process stabilizes for the different mortars. Knowing

the stabilization point is fundamental to fully assessing the long-term performance of mortars and optimizing their formulations for better water resistance. An optimization method must therefore be devised in order to determine an ideal combination of BSG, finer sand and w/c ratio for each use case, building on the foundation established by the top performers found in this study.

Regarding thermal analysis, the thermal conductivity of the BGS mortars will be determined using a standard procedure (e.g., per ISO 8301/ASTM C177 [40,41]) to better compare them to other thermal mortars and obtain, tentatively, a commercially ready product.

Determining the ideal percentage of BSG and w/c ratio will allow us to obtain BSG mortars with better performance. In addition, a comparative study with other sustainable aggregates, such as timber waste, can also be performed. Moreover, other binders can be tested to design mortars for different environments, such as hydraulic lime, lime and clay.

This additional information can help to refine BSG and sand mixtures, as well as enable improvements to be made to commercial mortars to achieve similar or superior performance to NHL–cork (used here as a benchmark, given that cement–PS is far from a sustainable option). In short, the results indicate that the use of BSG can significantly improve the water absorption properties of mortars, bringing them closer to the desirable characteristics found in NHL–cork.

This material is a remarkable example of the intelligent reuse of industrial by-products, as it not only improves operational efficiency but also contributes to the reduction of waste and its environmental impact. Finally, it is important to stress that these mortars, being biobased materials, can contribute to improving the thermal performance of buildings and represent a step in the direction of net-zero energy buildings.

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References

1. United Nations Environment Programme. *Global Status Report for Buildings and Construction—Beyond Foundations: Mainstreaming Sustainable Solutions to Cut Emissions from the Buildings Sector*; United Nations Environment Programme: Nairobi, Kenya, 2024.
2. IPCC. *Summary for Policymakers. An IPCC Special Report on the Impacts of Global Warming of 1.5 °C Above Pre-Industrial Levels and Related Global Greenhouse Gas Emission Pathways, in the Context of Strengthening the Global Response to the Threat of Climate Change, Sustainable Development, and Efforts to Eradicate Poverty*; Cambridge University Press: Cambridge, UK; New York, NY, USA, 2018; pp. 1–24. [[CrossRef](#)]

3. Parvin, K.; Hossain, M.; Arsad, A.; Ker, P.J.; Hannan, M. Building energy technologies towards achieving net-zero pathway: A comprehensive review, challenges and future directions. *J. Build. Eng.* **2025**, *100*, 111795. [CrossRef]
4. Ibrahim, M.; Harkouss, F.; Biwole, P.; Fardoun, F.; Ouldboukhite, S. Building retrofitting towards net zero energy: A review. *Energy Build.* **2024**, *322*, 114707. [CrossRef]
5. Shirinbakhsh, M.; Harvey, L.D. Net-zero energy buildings: The influence of definition on greenhouse gas emissions. *Energy Build.* **2021**, *247*, 111118. [CrossRef]
6. Krajewska, A.; Siewczyńska, M. Circular Economy in the Construction Sector in Materials, Processes, and Case Studies: Research Review. *Sustainability* **2025**, *17*, 7029. [CrossRef]
7. Bourbia, S.; Kazeoui, H.; Belarbi, R. A review on recent research on bio-based building materials and their applications. *Mater. Renew. Sustain. Energy* **2023**, *12*, 117–139. [CrossRef]
8. Horn, P.A.; Pedron, N.B.; Junges, L.H.; Rebelo, A.M.; da Silva Filho, H.H.; Zeni, A.L.B. Antioxidant profile at the different stages of craft beers production: The role of phenolic compounds. *Eur. Food Res. Technol.* **2021**, *247*, 439–452. [CrossRef]
9. Olajire, A.A. The brewing industry and environmental challenges. *J. Clean. Prod.* **2020**, *256*, 102817. [CrossRef]
10. Heumann, A. *Brewery's Spent Grain: Market Situation and Example of Valorisation*; B-Resilient, Co-Funded by the European Commission, Grant Agreement 101074621. Available online: <https://pole-innovalliance.com/wp-content/uploads/2023/05/Brewerys-Spent-Grain-Market-situation-and-example-of-valorisation-1.pdf> (accessed on 7 August 2025).
11. Zeko-Pivač, A.; Tišma, M.; Žnidaršič-Plazl, P.; Kulisić, B.; Sakellaris, G.; Hao, J.; Planinić, M. The potential of brewer's spent grain in the circular bioeconomy: State of the art and future perspectives. *Front. Bioeng. Biotechnol.* **2022**, *10*, 870744. [CrossRef] [PubMed]
12. Allegretti, C.; Bellineto, E.; D'Arrigo, P.; Griffini, G.; Marzorati, S.; Rossato, L.A.M.; Ruffini, E.; Schiavi, L.; Serra, S.; Strini, A. Towards a complete exploitation of brewers' spent grain from a circular economy perspective. *Fermentation* **2022**, *8*, 151. [CrossRef]
13. Duarte, L.C.; Esteves, M.P.; Carvalheiro, F.; Vicente, P.; Gírio, F.M. Os sub-produtos de natureza lenhocelulósica: Caracterização da situação portuguesa. *Eng. Química* **2007**, *5*, 56–62.
14. Błaszak, B.; Demir, İ.E.; Długosz, A.; Kołacz, P.; Bąk, M.; Gozdecka, G.; Kaniewski, W.; Szulc, J. Sustainable Processing of Brewers' Spent Grain for Plant-Based Yogurt Alternatives. *Sustainability* **2025**, *17*, 4087. [CrossRef]
15. Chu, H.-Y.I.; Miri, T.; Onyeaka, H. Valorization of Bioactive Compounds Extracted from Brewer's Spent Grain (BSG) for Sustainable Food Waste Recycling. *Sustainability* **2025**, *17*, 2477. [CrossRef]
16. Ferraz, E.; Coroado, J.; Gamelas, J.; Silva, J.; Rocha, F.; Velosa, A. Spent brewery grains for improvement of thermal insulation of ceramic bricks. *J. Mater. Civ. Eng.* **2013**, *25*, 1638–1646. [CrossRef]
17. Muthuminal, R.; Priya, R.M. Experimental investigation on utilization of brewers waste as fine aggregate in concrete. *Mater. Today Proc.* **2023**; in press. [CrossRef]
18. El Haddaji, B.; Benzaama, M.-H.; Quiertant, M.; El Mendili, Y. Insight into the use of brewers' spent grain as a low-carbon aggregate in building materials. *Biomimetics* **2024**, *9*, 781. [CrossRef]
19. Alene, T.E.; Lemlemu, T.A.; Yifru, B.W. Study on the Effect of Partial Replacement of Cement by Breweries Dry Grain (Sorghum) Ash in Mortar Property. *Adv. Mater. Sci. Eng.* **2025**, *2025*, 5667403. [CrossRef]
20. Costa, H. *Betões Estruturais e Agregados Leves. Aplicações em Prefabricação e Reforço de Estruturas*. Ph.D. Thesis, Universidade de Coimbra, Coimbra, Portugal, 2012.
21. Coutinho, J.d.S. *Agregados para Argamassas e Betões*. 2002, pp. 105–125. Available online: https://civil.fe.up.pt/pub/apoio/ano1/cienciadosmateriais/apontamentos/teorica_20022003/JSC_105a125.pdf (accessed on 30 June 2025).
22. Manso, M.; Castro-Gomes, J. Design of alkali-activated materials for a modular green wall and green roof system. *MATEC Web Conf.* **2019**, *274*, 04001. [CrossRef]
23. Jerónimo, A.; Soares, C.; Aguiar, B.; Lima, N. Hydraulic lime mortars incorporating micro cork granules with antifungal properties. *Constr. Build. Mater.* **2020**, *255*, 119368. [CrossRef]
24. Sousa, A. *Aplicação de Argamassas Leves de Reboco e Assentamento em Alvenarias*; Faculty of Engineering, University of Porto: Porto, Portugal, 2010.
25. Morgado, A. *Durabilidade de Argamassas Térmicas com Agregados Leves e Isolantes*; Instituto Superior Técnico: Lisbon, Portugal, 2017.
26. Thiedeitz, M.; Ostermaier, B.; Kränkel, T. Rice husk ash as an additive in mortar—Contribution to microstructural, strength and durability performance. *Resour. Conserv. Recycl.* **2022**, *184*, 106389. [CrossRef]
27. Marques, B.; Almeida, J.; Tadeu, A.; António, J.; Santos, M.I.; de Brito, J.; Oliveira, M. Rice husk cement-based composites for acoustic barriers and thermal insulating layers. *J. Build. Eng.* **2021**, *39*, 102297. [CrossRef]
28. Wang, Z.; Zhao, Y.; Zhou, L.; Xu, L.; Diao, G.; Liu, G. Effects of hydroxyethyl methyl cellulose ether on the hydration and compressive strength of calcium aluminate cement. *J. Therm. Anal. Calorim.* **2020**, *140*, 545–553. [CrossRef]
29. Badagliacco, D.; Sanfilippo, C.; Megna, B.; La Mantia, T.; Valenza, A. Mechanical and thermal properties of insulating sustainable mortars with *Ampelodesmos mauritanicus* and *Pennisetum setaceum* plants as aggregates. *Appl. Sci.* **2021**, *11*, 5910. [CrossRef]

30. EN 998-1; Specification for Mortar for Masonry—Part 1: Rendering and Plastering Mortar. European Committee for Standardization: Brussels, Belgium, 2016.
31. EN 1097-5; Tests for Mechanical and Physical Properties of Aggregates—Part 5: Determination of the Water Content by Drying in a Ventilated Oven. European Committee for Standardization: Brussels, Belgium, 2008.
32. EN 933-1; Tests of the Geometric Properties of Aggregates. Part 1. Particle Size Analysis. Sieving Method. European Committee for Standardization: Brussels, Belgium, 2014.
33. EN 1097-3; Tests for Mechanical and Physical Properties of Aggregates—Part 3: Determination of Loose Bulk Density and Voids. European Committee for Standardization: Brussels, Belgium, 1998.
34. EN 1015-3; Methods of Test for Mortar for Masonry—Part 3: Determination of Consistence of Fresh Mortar (by Flow Table). European Committee for Standardization: Brussels, Belgium, 2006.
35. EN 1015-18; Methods of Test for Mortar for Masonry—Part 18: Determination of Water Absorption Coefficient Due to Capillary Action of Hardened Mortar. European Committee for Standardization: Brussels, Belgium, 2002.
36. EN 1015-11; Methods of Test for Mortar for Masonry—Part 11: Determination of Flexural and Compressive Strength of Hardened Mortar. European Committee for Standardization: Brussels, Belgium, 2019.
37. Bamforth, C.W. *Beer: Tap into the Art and Science of Brewing*; Oxford University Press: New York, NY, USA, 2009; ISBN-10: 978-0195305425.
38. Castro, L.E.N.; Colpini, L.M.S. All-around characterization of brewers' spent grain. *Eur. Food Res. Technol.* **2021**, *247*, 3013–3021. [[CrossRef](#)]
39. Lazera, R.F. Avaliação do Desempenho Mecânico de Argamassas Térmicas em Protótipos de Parede. Master's Thesis, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal, 2016.
40. ISO 8301:1991; Thermal Insulation—Determination of Steady-State Thermal Resistance and Related Properties—Heat Flow Meter Apparatus. International Organization for Standardization: Geneva, Switzerland, 1991.
41. ASTM C177-19; Standard Test Method for Steady-State Heat Flux Measurements and Thermal Transmission Properties by Means of the Guarded-Hot-Plate Apparatus. ASTM: West Conshohocken, PA, USA, 2019.

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