Construction and Building Materials 419 (2024) 135435

Contents lists available at ScienceDirect

Construction and Building Materials

journal homepage: www.elsevier.com/locate/conbuildmat

Characterization and performance of building composites made from gypsum and woody-biomass ash waste: A product development and application study

Manuel Alejandro Pedreño-Rojas [a], César Porras-Amores [a], Paola Villoria-Sáez [a,*], María Jesús Morales-Conde [b], Inês Flores-Colen [c]

[a] TEMA Research Group, ETS Edificación, Universidad Politécnica de Madrid, Av. Juan de Herrera 6, Madrid 28040, Spain
[b] Departamento de Construcciones Arquitectónias I, ETS Arquitectura, Universidad de Sevilla, Av. Reina Mercedes 2, Seville 41013, Spain
[c] CERIS, Department of Civil Engineering, Architecture and Environment, IST, Universidade de Lisboa, Av. Rovisco Pais, Lisbon 1049-001, Portugal

ARTICLE INFO

Keywords:
Plaster
Recycling
Circular economy
Wood
Ash
Construction

ABSTRACT

The aim of this study is to explore the potential of using biomass-ash waste as a secondary raw material for building composites. The waste is generated by a thermal power plant that burns woody biomass and would otherwise be disposed of in landfills. The study investigates the physical and mechanical properties of gypsum-based composites containing different proportions of biomass-ash waste and compares them with the reference and regulatory documents. The study also proposes some possible building applications for the optimal composite and evaluates its performance through simulations. The results indicate that adding up to 25% wood ash can improve the mechanical strength of the composites, exceeding the reference and minimum requirements. The proposed building applications using the new composite reach a reduction in the environmental impact and an improvement in the energy efficiency of the building envelope.

1. Introduction

The construction industry is the single largest global consumer of resources and raw materials [40]. This is not the only negative impact, but also, in most cases, the construction process comes from non-renewable resources, and uses considerable amounts of energy, since some of the materials are subjected to energy-intensive manufacturing process, along with the significant volume of emissions of all types of pollutants. Therefore, several researchers have claimed that buildings are responsible of accounting for around 40% of total energy use, consume 12% of the world's drinkable water, and produce almost 40% of global carbon dioxide emissions in Europe [12].

This situation is expected to worsen, as the world's consumption of raw materials is set to nearly double by 2060 as the global economy expands and living standards rise [26]. In this way, the construction industry needs to change and move toward other activities that promote positive impacts on society and the environment [13].

In the attempt to provide an alternative to the traditional and dominant model featured at consuming and disposing of resources, the Circular Economy (CE) initiative emerges for transitioning to a more efficient circular model driving the research toward the minimizing, recycling, and reusing of waste streams [2,25]. In this way, CE has the ultimate goal of retaining materials and resources circulating at their highest value within planetary boundaries, in a way that additional natural resources are unnecessary to produce goods, and the discarded materials are not viewed as waste [22].

Since 2015, the European Commission has adopted several Circular Economy Action Plans in order to help stimulate Europe's transition to a circular economy, by proposing a global alliance to identify knowledge and future challenges in advancing towards a global circular economy [17].

In this regard, developing new regulations and policies, decreasing the exploitation of natural resources, optimizing production processes, establishing commercial competitiveness for recovered and recycled materials, as well as diminishing the use of natural resources throughout the entire construction process are actions aligned with CE that need to be considered by government agencies, private companies, and researchers.

In this context, investigating the potential to reduce material used in this sector, by consuming secondary or waste products, will significantly

* Corresponding author.
E-mail address: paola.villoria@upm.es (P. Villoria-Sáez).

https://doi.org/10.1016/j.conbuildmat.2024.135435
Received 30 October 2023; Received in revised form 22 January 2024; Accepted 9 February 2024
Available online 20 February 2024

impact global raw material consumption and reduce the pressure on natural resources, favoring the transition towards CE [22].

For this purpose and aiming to reduce the construction industry's impacts, the use of recovered and recycled materials to produce new construction products has arisen in the past decade. Current statistics show that the EU's circularity rate has risen during the last ten years, from 10.8% in 2010 to 11.7% in 2021 [18]. A higher circularity rate value indicates a higher primary raw materials substitution by secondary materials. However, this rate is well below the target set by the EU for 2030 (24.3%) and therefore new options for waste recovery and recycling should be encouraged.

Currently, as a recycling strategy, building products incorporate a fraction of recycled materials such as concrete, glass, plastics, tires, wood, among others, in an effort of recovering what is often discarded. In this way, with the ever-increasing need to reduce the dependency on fossil fuel combustion and lower greenhouse gas emissions, the use of biomass for heat and electricity production have increased substantially, resulting in an increase of ash waste generation. Almost 500 million tons of biomass ash are produced per year worldwide, and for the most part (around 70%) are disposed of in landfills [14] and the rest is used for soil pH correction and/or fertilization or for incorporation in cementitious materials for building and road constructions.

2. Literature review

Many researchers have focused on the addition of waste ashes as alternative raw material to produce building materials and products. Among these studies, those incorporating ashes from the agricultural, wood or other industrial sectors can be highlighted (Table 1).

Regarding the waste from the agro-industrial sector, ashes from the production of olives, rice husk, and palm oil have been widely used for building applications showing lower densities and improved thermal properties in the developed composites [15,31]. In particular, up to 8% of rice husk ash can be incorporated in gypsum keeping an adequate workability, reducing the density and improving the thermal properties of traditional building plasters [28]. In addition, a good fire reaction was observed when olive pomace or palm oil ashes were used to develop building panels and boards [10,30]. A high water retention capacity was achieved when ashes from the palm oil extraction were used to manufacture boards containing clay, gypsum and vermiculite [10].

Other authors analyzed the viability of incorporating other industrial ashes in building materials to improve some properties [27,34,35,41]. Low thermal conductivity coefficients and higher sound-absorbing properties were observed by Leiva et al. [29] when fly ash from coal combustion was incorporated in a gypsum matrix, keeping similar mechanical properties to other lightweight commercial gypsum products. By contrast, lower mechanical properties were achieved when 60% of the natural gypsum was substituted by white slag ash [9], but they were all above the minimum set by the regulations. Despite the lower mechanical resistances, a substantial improvement of the fire reaction was observed when higher amount of slag ash was incorporated.

Furthermore, several publications were found incorporating wooden biomass ash in building materials. Fořt et al. [19] explored the effect of replacing 50% of wooden biomass ash in lime plasters to be applied as an exterior surface layer in buildings. A considerably improvement on the mechanical properties was observed, whereas the hygric properties were kept similar to the reference. In addition, better mechanical improvements (around 17% compared to the reference) were also observed when 20% of wooden biomass ash was incorporated in cement [21]. Fořt et al. [20] also explored the viability of using wooden biomass ash as supplementary cementitious material, by replacing up to 30% of coal fly ash in the fabrication of blended cements.

Table 1 summarizes the key findings from the literature review conducted to determine what has been previously investigated on the incorporation of ash waste in building materials. In general, the findings obtained by the studies shown in Table 1 have similar or slightly better properties than conventional ones. They are characterized for having:

- higher mechanical performance;
- low thermal conductivity;
- good fire reaction; and
- improved acoustic insulation.

Based on these findings some authors have explored the viability of combining a mix of various ashes. Resulting in similar properties than the ones above, such as higher water retention [38], acceptable and improved mechanical properties [8,38] and good thermal and fire reaction [8].

However, it is necessary to study the incorporation of other types of biomass ashes in gypsum since, having a very different composition, it will provide different properties [38]. In this sense, despite the numerous investigations found adding ashes, no previous investigations have been found incorporating biomass ash from wood in plaster composites.

Given the above background, this work aims to contribute to the development of sustainable materials by developing a gypsum material containing woody biomass waste to improve the characteristics of regular gypsums. Therefore, the objective of the study is to assess the mechanical behavior of gypsum composites incorporating woody biomass ash waste and analyze the possible building application.

3. Materials and methods

3.1. Materials

The materials used for this study were: gypsum, woody biomass ash, and water:

- Gypsum: The gypsum used is high purity gypsum named Iberyola E-30/E-35, which is compliant with the standard UNE-EN 13279-1 [4] and classified as type A by the European classification. It was provided by Placo Saint-Gobain.
- The biomass ash shown in Fig. 1 was collected from a district heating power plant - fueled by woody biomass - placed in Móstoles (Spain). Its real density, determined by Mastersizer equipment, was 2.4108 g/cm^3, with a coefficient of variation of 0.0564%. The particle size distribution of the ash was also obtained, and it is represented in Fig. 2. The chemical composition of the biomass ash was obtained by a PANalytical XRD equipment, as it is shown in Fig. 3, were the major components were graphite and quartz followed by portlandite and calcite.
- Water: Regular water from Canal de Isabel II was used.

3.2. Experimental plan

The experimental plan was developed following the next phases:

1. Samples' preparation;
2. Physical and mechanical characterization;
3. Raw material consumption and selection of best composite;
4. Proposal for building applications and further characterization.

3.2.1. Samples' preparation

The samples' preparation followed the standard UNE-EN 13279–1 [4], and it began with the elaboration of the reference (without any waste) and continued with the preparation of composites incorporating different percentages of ash waste (5%; 10%; 15%; 20% and 25%) over the weight of gypsum. A total of six different composites were analyzed (Table 2). According to the studies found in the literature review (Table 1) and the supplier's recommendation, the water/gypsum (w/g) ratio used in this research was 0.8.

Table 1
Key findings of previous research works incorporating waste ashes in gypsum composites.

Waste origin	Reference	Waste ash	% waste	Matrix	Building application	Key findings
Agro-industrial	Vilches et al. [38]	Biomass ash: Olive pomace and rice-husk	69% pomace. 1% rice-husk. 1% glass fiber	Gypsum	Insulating plates with fire-resistance properties	The developed product presents similar fire resistance and physical and mechanical properties to other commercial products used in passive fire protection in buildings and industrial installations
	Leiva et al. [30]	Biomass ash: olive oil extraction process.	60% ash. 9.5% vermiculite 0.5% fiber	Gypsum	Low-density panels (800 kg/m3) for internal partitions in buildings	Good fire resistance due to their high-water retention capacity (similar to gypsum plasterboard). It did not show noticeable deformation, crumbling, or cracking.
	Alba et al. [8]	Fly ash from olive oil extraction	50% ash.	Gypsum, clay, and cement with fibers	Internal wall partitions or limited load-bearing properties	Low density. Resistance strength decreases with more addition of ash
	Amat et al., [10]	Fly ash from oil palm extraction	< 20% ash	Gypsum	Wallboard use for on walls, ceilings, or partitions	biomass ash panel board can retain more than 2 h fire resistance in standard conditions of room temperature by fire laboratory and panels showing a compressive strength of 3.54 MPa
	Leiva Aguilera y Del Río Merino (2014)	Rice husk ash	8% ash	Gypsum	Suspended ceiling	Reduced density and improved thermal behavior and mechanical properties keeping a good workability.
Other industries	Rodríguez et al. (2009)	Ladle furnace slag	30%	Cement	Masonry mortars	Higher mechanical properties are achieved when higher % of ash is incorporated.
	Leiva et al. [29]	Fly-ash from coal combustion	60% ash	Gypsum Vermiculite Fibres	Fly-ash boards	Good physical and mechanical properties. Sound-absorbing material. Low thermal conductivity and high fire reaction.
	Rahamma et al. (2015)	Fly-ash	30%	Cement	Cement binders	Higher amount of fly ash required grater water to keep the workability and higher setting time.
	Záleská (2018)	Sewage sludge	30% ash	Cement	Lime and cement binders	The increase in porosity up to 6% and decrease in compressive strength up to 3% were satisfactory.
	Alonso et al. [9]	White slag	60% ash	Gypsum	Indoor partitions or protection in areas with aggressive thermal requirements	Mechanical results decreased compared to reference. Better behavior before fire.
	Kua and Choo [27]	Biochar-coated pellets	0.38%	Lime	Indoor lime plasters	The paper evaluates the potential of removing CO_2 when biochar is used and aggregate in indoor plasters.
Wood	Fořt et al. [19]	Wooden biomass ash	50% ash	Lime	Exterior superficial layer	Mechanical performance improved considerably, and the rest of the results (hygric and porosity) were kept similar to the reference in all cases.
	Fořt et al. [21]	Wooden biomass ash	70% ash	Cement	Non-structural concrete	Higher mechanical resistance when up to 30% of the cement was replaced
	Fořt et al. [20]	Wooden biomass ash	30% ash	Cement	Cement mortars	Wooden biomass ash can be used as supplementary cementitious material and substitute up to 30% of coal fly ash.

Fig. 1. Woody biomass ash (WBA).

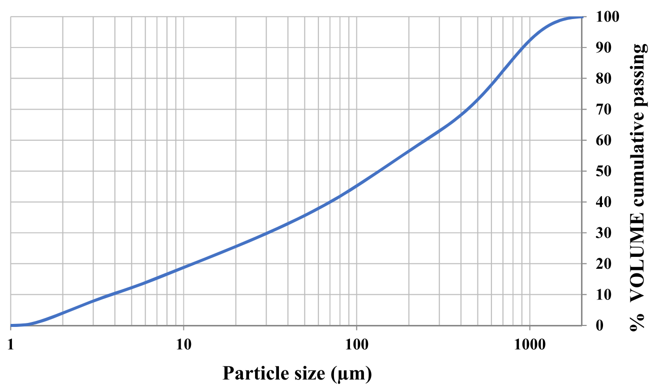

Fig. 2. Particle size distribution for the woody biomass ash (WBA).

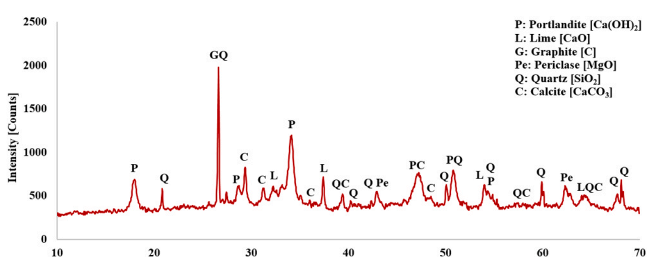

Fig. 3. X-ray diffraction obtained for the woody biomass ash (WBA).

Table 2
Composite's composition for 1 kg of gypsum powder.

Composite	Gypsum [g]	Water [g]	W/G ratio	Wooden biomass ash (WBA) [g]
Ref	1000	800	0.8	0
WBA5	1000	800	0.8	50 (5 wt%)
WBA10	1000	800	0.8	100 (10 wt%)
WBA15	1000	800	0.8	150 (15 wt%)
WBA20	1000	800	0.8	200 (20 wt%)
WBA25	1000	800	0.8	250 (25 wt%)

Samples were left to harden for seven days at room temperature in the laboratory with a temperature of 23 ± 2 °C and air relative humidity around 50 ± 5%. On the seventh day, they were introduced and kept in the oven at 40ºC for 24 h before testing.

3.2.2. *Physical and mechanical characterization*

Experimental tests in the laboratory were conducted aiming to determine the physical and mechanical properties of the composites. The following tests were carried out: dry bulk density, superficial hardness, flexural strength, compressive strength; bonding strength, and thermal conductivity test, following the UNE EN 102042 [7], UNE EN 13279–2 [3] and ASTM D5334–08 [11] standards.

Three specimens 4×4x16 cm^3 of each composite were tested for dry bulk density, superficial hardness, flexural and compressive strength (a total of 18 specimens were tested in each test). For this, a Gibertini Europe3000HR scale was used for the bulk density, a Shore C durometer for the superficial hardness and the universal testing machine Ibertest Autotest 20 was used for the flexion and compression strength.

For the bonding test, each composite –in fresh state– was layered over a ceramic-based support creating a coating of 1 cm thick. Then, nine circular segments were marked on the surface of each composite (a total of 54 samples), and metallic discs with a diameter of 5 cm were fixed on top. Then, a Dynatest DTH 500 device was used to perform the test and record each value following the UNE EN 13279–2 [3] standard.

To obtain the thermal conductivity coefficient, one specimen of 6×6x3 cm^3 per composite (a total of 6 samples) was developed and tested (3 measurements) using an ISOMET 2114 transient equipment to measure the thermal conductivity coefficient under laboratory conditions, following the procedure defined by ASTM D5334–08 [11].

Results were recorded and the mean value was achieved for each composite. Results were compared with the reference sample and with the minimum values set by the standards.

Finally, in order to justify the obtained results, SEM analysis of the composites was conducted using a FEI TENEO, an ultra-high-resolution analytical Scanning Electron Microscope.

3.2.3. *Analysis of the consumption of natural gypsum and selection of composite*

In this section, the most sustainable composite was selected considering the environmental performance (higher waste content) and mechanical behavior (good mechanical properties fulfilling gypsum composites regulations).

For this, an analysis of the raw material consumption was explored following the method used by previous research works [32,36,39]. The reduction in percentage of the consumption of natural gypsum compared to the reference sample was calculated for all the composites. After that, the environmental benefits of the achieved gypsum reduction was calculated using the Global Warming Potential (GWP) and Embodied Energy (EE) impacts according to ITeC-BEDEC database [24].

3.2.4. *Proposal for building product and further characterization*

After selecting the most suitable composite, a new building product for interior coatings in buildings were experimentally and numerically evaluated. In a first phase, a laboratory procedure was conducted, in which two 60×40×1.5 cm^3 panels were developed using the selected composite and the reference composition and were further tested regarding their mechanical resistance to bending following UNE-EN 12859 [6].

After that, trying to evaluate other commercial panel dimensions, finite elements models were elaborated, and using the breaking test results above described to calibrate them, a mechanical simulation of a bending test was conducted using SAP2000 software. On it, three different panel dimensions were evaluated for both compositions: 60×40×1.5 cm^3 (the one tested in laboratory), 60×60×1.5 cm^3 (standard size for suspended ceiling tiles) and 60×120×1.5 cm^3 (typical in continuous ceilings pieces). The achieved values were compared and checked with the standard requirements for each case.

3.2.5. *Proposal for building product and energy efficiency*

A building energy simulation was also done using Design Builder software to evaluate the energy efficiency potential when recycled material is applied to a reference building. The simulation model developed will serve to quantify the energy savings involved in including the same recycled material in different building applications (gypsum plaster, laminated gypsum board, and gypsum block) replacing traditional materials.

For this purpose, a virtual reference building has been developed with representative characteristics of a large part of the buildings built in Spain. The reference building includes the most common construction characteristics in Spain [23] and the regulatory requirements established in the Technical Building Code [37]. All details of the construction model, as well as the settings of the energy simulation used, can be consulted in the article previously published by Porras-Amores et al. [33]. In this sense, the composition of the façade of the building has been slightly modified to adapt the case study to the new recycled materials included in this research and carry out the comparative study.

The building has been virtually located and simulated in a cold climate (Soria) and a warm climate (Seville), which represent the climate variability in Spain, in order to study the potential of the recycled materials in different climate conditions. According to the Köppen climate classification, Soria corresponds to a temperate oceanic climate (Cfb) and Seville to a typical Mediterranean climate (Csa).

Fig. 4 shows the geometry of the simulation model developed. The reference building has four floors with a free height of 2.7 m each and there are no floors below ground level. Each floor is made up of six equal dwellings of 110 m^2 each, resulting in a total useful area of 2640 m^2 in the building. The total façade area is 1484 m^2 while the glazing area is 287 m^2 (20% of the total).

4. Results and discussion

4.1. Physical and mechanical characterization

The results of the physical and mechanical tests performed for the composites' characterization are shown in Table 3.

The obtained results of the dry bulk density, with uncertainty, are represented in Fig. 5. As shown in the graph, samples with WBA have slightly higher bulk density compared to the reference without any additions. The sample with the highest density value was WBA20, with around + 21% higher density than the reference sample, + 12% higher than WBA5 and + 7% related to WBA10 and WBA15 composites. On the other hand, WBA25 composite experienced a drop in density of 10% compared to WBA20 being only + 9% higher than the reference sample. Also, it should be noted that none of the composites can be considered lightweight composites as the bulk density surpass 0.8 g/cm^2 in all cases [1].

Fig. 6 shows the superficial hardness of each composite. Low amount of waste additions –WBA5 and WBA10- result in similar or even lower superficial hardness than the reference (−11% for WBA10 and −5% for WBA5). By contrast, when more than 10% of WBA is added, higher superficial hardness is recorded, reaching around + 11% of increase for the WBA25 composite and + 4% for the WBA20 composite, compared to the reference sample. All of the achieved values are above the minimum value − 45 Shore C units- required by the regulation [3,16].

Regarding the results for flexural strength (Fig. 7), all the composites showed a decrease compared to the reference mixture. In this case, WBA10 composite presented the lowest value with a decrease by up to − 49% or WBA25 composite with a decrease of − 46%. On the other hand, WBA5 and WBA15 results experimented a drop of-37% and − 38% respectively compared to the reference mixture. In the middle, WBA20 composite showed a decrease of − 40% according to the reference composite value. Despite these drops in resistance, the values always remained above the minimum value − 1 MPa- required by the regulation UNE-EN 13279–1 [4]. These results are in line with previous research works. In particular, a reduction in the flexural strength was also observed by Alonso et al. [9], when white slag ash was incorporated in gypsum composites.

Similarly, the same tendency was observed for the values obtained in the compressive strength test (Fig. 8), decreasing up to 49% - also for the WBA10 composite -, when compared to the reference value (4.08 MPa). In this case, WBA15 and WBA25 composites showed similar drops in resistance, around − 40% compared to the reference mixture. However, it should be noted that they all remained above 2 MPa, which is the minimum required by the standard UNE-EN 13279–1 [4,5]. Except for the reference, the best performing composite was WBA20, achieving 5.58 MPa (33.7% lower than the reference).

Fig. 9 presents the results obtained for the bonding strength of the composites, obtained using the adhesive pull-off test, which are similar to those of the reference. The composites with higher bonding strength were WBA15 and WBA20 (+ 8.33% and +16.7%, respectively if compared to the reference). By contrast, the composite with the lowest bonding strength was WBA25 (−8.3%).

Fig. 10 shows the results obtained for the thermal conductivity measurement. As it can be noticed, an improvement of the thermal behavior of the composite was observed when the amount of wood

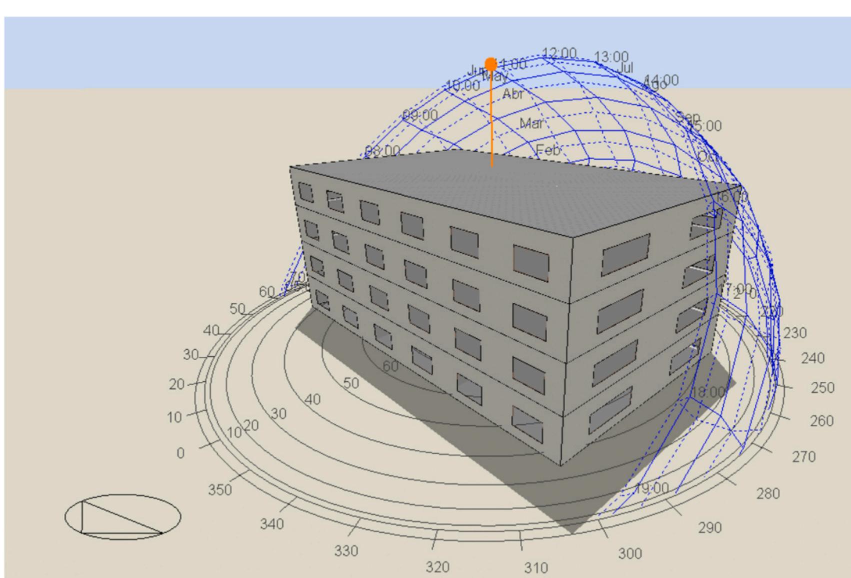

Fig. 4. Building energy simulation model.

Table 3
Results of the physical and mechanical tests, including coefficient of variation [%].

Sample	Dry bulk density [g/cm^3]	Superficial hardness [Shore C]	Flexural strength [MPa]	Compressive strength [MPa]	Bonding strength [kN]	Thermal conductivity [W/ (m·K)]
Ref	0.988 (4.72%)	68.192 (4.63%)	3.554 (6.17%)	8.423 (5.98%)	0.300 (6.29%)	0.300
WBA5	1.071 (5.07%)	65.067 (4.87%)	2.245 (6.38%)	4.583 (6.11%)	0.288 (6.45%)	0.281
WBA10	1.121 (5.21%)	60.700 (5.19%)	1.843 (6.64%)	4.083 (6.29%)	0.300 (6.78%)	0.278
WBA15	1.121 (5.40%)	68.700 (5.38%)	2.209 (7.11%)	5.032 (6.86%)	0.325 (7.12%)	0.262
WBA20	1.202 (5.68%)	70.900 (5.41%)	2.133 (6.98%)	5.584 (6.70%)	0.350 (7.33%)	0.257
WBA25	1.084 (5.73%)	75.867 (5.59%)	1.907 (7.19%)	5.195 (7.01%)	0.275 (7.41%)	0.247

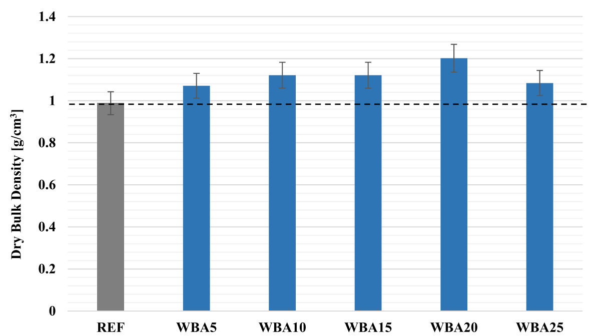

Fig. 5. Dry bulk density results of the composites with coefficient of variation.

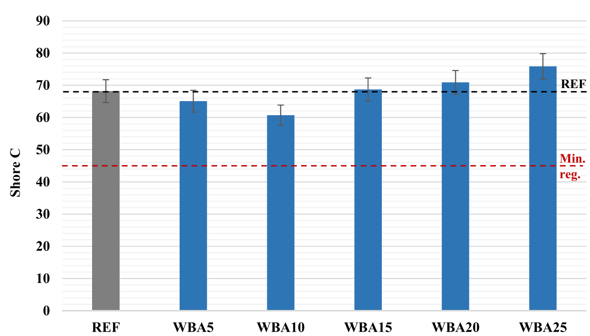

Fig. 6. Superficial hardness results for each composite with coefficient of variation.

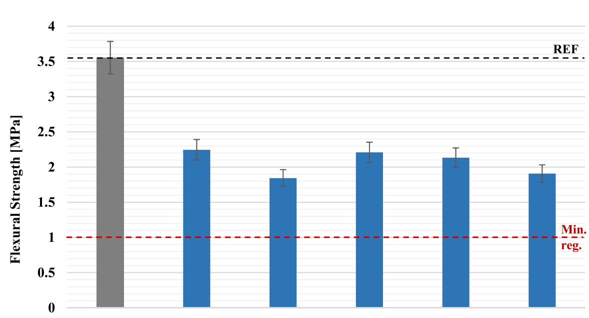

Fig. 7. Flexural strength results for each composite with coefficient of variation.

biomass ash increased in the mixture, achieving the best the performance with 25% of WBA addition (WBA25) (−17.7%, if compared to the reference value). In this case, it must be noted that no significance

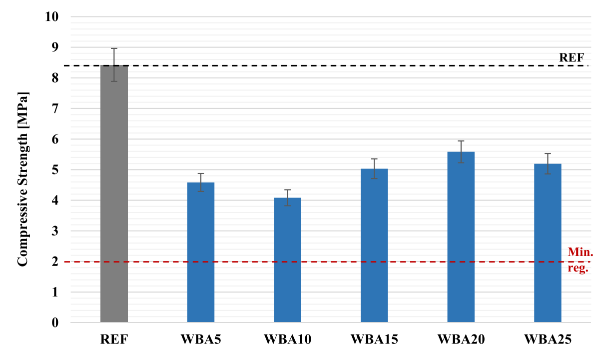

Fig. 8. Compressive strength results for each composite with coefficient of variation.

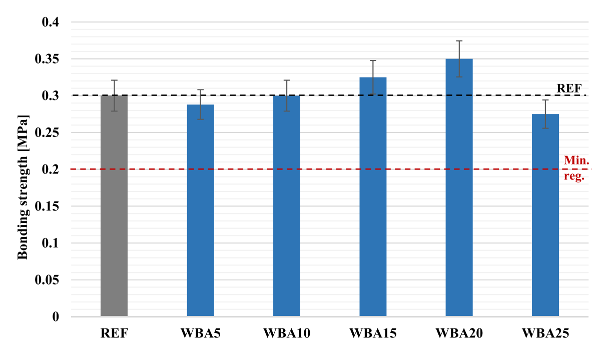

Fig. 9. Bonding strength results for each composite with coefficient of variation.

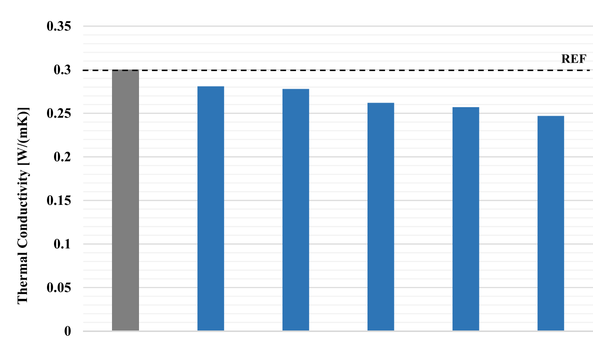

Fig. 10. Thermal conductivity coefficient results.

standard deviation was observed for any composites when the three measurements values were evaluated. An improvement in the thermal conductivity was also found by previous research works incorporating ashes from the olive and rice production, which claimed lower thermal conductivity coefficients compared to the reference [10,28,30].

Fig. 11 shows the relation between the dry bulk density and the thermal conductivity of each composite. Results show that the observed drop on the thermal conductivity of the plaster was only explained by the increase on the percentage of WBA added to the compositions. However, not for all the plasters, the drop on the dry bulk density did not follow the same tendency for the thermal behavior.

Finally, to justify some of the noticed mechanical behavior on the plasters, SEM analysis was conducted. Fig. 12 presents two SEM images taken from WBA25 plaster. As in can be seen, the addition of wood biomass ash increases the porosity of the plaster, improving its thermal performance. Furthermore, the lack of adherence between the WBA particles and the gypsum matrix could justify the drop on the mechanical properties of the new composites.

4.2. Analysis of the consumption of natural gypsum

The addition of WBA particles of the gypsum matrix means a reduction on the consumption of natural gypsum on the plasters. Thus, Table 4 presents the reduction on the consumption of natural gypsum for a kg. of each composite and its implication in terms of GWP and EE [24].

As it was expected, the highest reduction was obtained for the WBA25 composite, achieving a reduction of − 0.012 kg CO_2 eq. and − 0.131 MJ of primary energy. This fact justifies the highest contribution of the gypsum powder in the environmental impact of the composites, improving them when waste is added as aggregate to the mixtures (reducing the amount of gypsum used).

4.3. Discussion on building applications – mechanical performance

As it was mentioned, the developed composites were used for the generation of gypsum plates for the cladding of buildings. Thus, on a first phase, Reference and WBA25 plates (60 ×40×1.5 cm^3) were produced and tested in laboratory, as it is shown in Fig. 13. In this procedure, the pieces were submitted to a bending strength test, reaching 1.12 and 0.74 MPa respectively.

Considering the bending strength tests results, after the laboratory breakage, a numerical finite element simulation of the bending strength test of the plates was conducted using SAP2000 software. To do it, three different plates length were tested: 40, 60 and 120 cm (Fig. 14). As it is shown in Fig. 15, all the simulation passed the values obtained for the tensile strength of the composites. Thus, it can be concluded that all the developed composites are suitable for its usage in gypsum covering plates for multiple uses according to the different sizes of the pieces: suspended ceiling tiles, continuous ceiling pieces, etc.

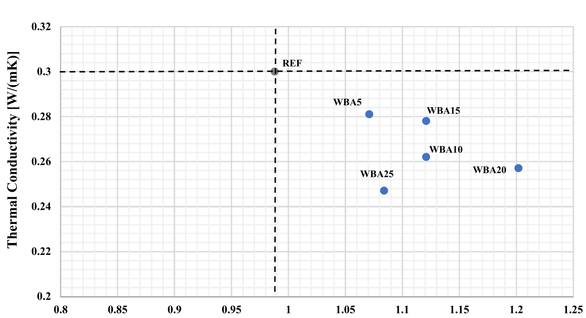

Fig. 11. Relationship between dry bulk density and thermal conductivity for each composite.

4.4. Discussion of energy efficiency potential

Once the characteristics of the reference building were defined and the thermal properties of the recycled material estimated (Fig. 10), the set of energy simulations began. To evaluate the energy efficiency potential of recycled material, only the composite with the best thermal insulation properties (WBA25) was used.

Two simulations were carried out for each location (Seville and Soria), one with the reference building (REF) using traditional materials and another incorporating recycled materials (WBA25) replacing some traditional materials of the interior cladding of the facade and roof. Specifically, the “double hollow brick” and the “gypsum plaster” of the façade were replaced by the “plaster block with 25% WBA” and the “gypsum plaster with 25% WBA”, respectively. In the same way, the “laminated gypsum board” of the false ceiling of the roof was replaced by the “laminated gypsum board with 25% WBA”.

Table 5 and Table 6 detail the materials used in the façade and flat roof of the reference building, together with the necessary data for the simulations (thickness, density, and thermal conductivity). The characteristics of the materials (thickness, density, and thermal conductivity) have been obtained according to information published by Spanish official institutions [37].

Both building elements incorporate plaster materials, which were replaced by recycled materials in the second simulation. The materials highlighted in green were used in the first simulation (REF) and later replaced by those highlighted in orange in the second simulation (WBA25). In contrast, the same materials were used in the basement in contact with the ground, in all simulations [33]. The recycled material has been included in the following building applications: gypsum plaster, laminated gypsum board, and gypsum block.

Before analyzing the results, it is worth remembering that energy losses in a building can occur due to the transfer of heat by transmission through the enclosure, or due to the heat transfer by transmission in the envelope. In the Spanish context, the Technical Building Code establishes that new buildings must comply with a minimum rate of air changes per hour that must be maintained naturally or mechanically. Furthermore, buildings always have water leakages that depend on multiple variables, such as the age of the building, the number of openings, or the quality of the execution of the construction elements.

Although the selected reference building is considered representative as it includes the most common construction characteristics in Spain, after carrying out several preliminary simulations, it has been seen that heat transfer in the building is mainly produced by air renewals. Therefore, the potential for energy savings is conditioned by the high rate of air renewals in the building, with 79% of energy consumption due to air renewals compared to 21% due to heat transfer through the envelope. This is mainly due to the current regulatory requirement of the Spanish Building Code [37] that requires permanent ventilation in the building for health reasons of the occupants.

Therefore, it is important to remember that the energy savings potential of recycled materials will be much higher in other buildings that have low air renewal rates, compared to those obtained in this research.

Table 7 compares the total savings in heating, cooling, and the sum of both in the two Spanish cities under study.

The results show that the recycled material improves the energy efficiency of buildings while offering a second life to an industrial by-product. The energy savings obtained in a standard Spanish building following the current building regulations range from 5% (warm climate) to 3% (cold climate), being greater in heating than in cooling in absolute terms. For example, in Soria, the incorporation of recycled material to replace traditional material has led to energy savings of 1630 kwh in heating and 106 kwh in cooling.

Furthermore, the economic savings of reducing energy consumption in cooling can reach 6% (Seville) to 15% (Soria), while in heating it can reach 3% (Soria) to 5% (Seville). These values could increase considerably in buildings or constructions with low ventilation rates, such as,

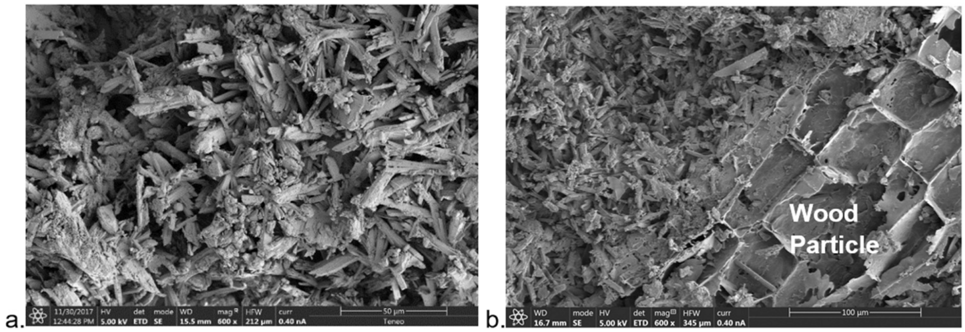

Fig. 12. SEM images obtained for the Reference (a) and WBA25 (b) composites.

Table 4
Results of the reduction of natural gypsum consumption per kg of composite and environmental repercussion.

Sample	Reduction of natural gypsum consumption [wt%]	Global Warming Potential (GWP) [kg CO_2 eq.]	Embodied Energy (EE) [MJ]
Ref	-	-	-
WBA5	2.8	0.005	0.051
WBA10	3.4	0.006	0.061
WBA15	4.7	0.008	0.085
WBA20	6.2	0.010	0.112
WBA25	7.3	0.012	0.131

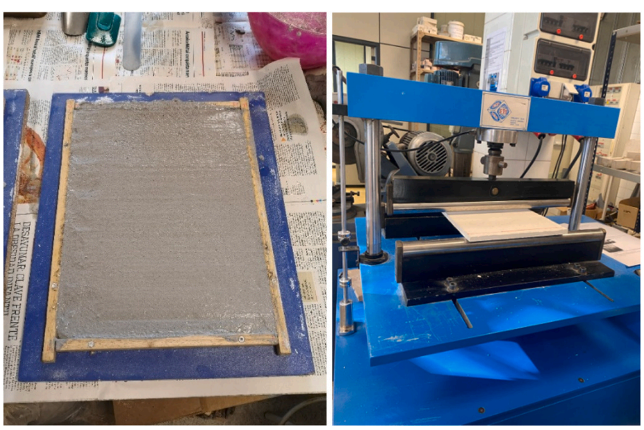

Fig. 13. Panel setting and bending strength test of 60 × 40×1.5 cm^3 gypsum panels.

for example, in warehouses that do not need ventilation or in countries exempt from regulations that require ventilation (or with low requirements).

Results from the energy simulations are applicable to a temperate oceanic climate (Cfb) and to a typical Mediterranean climate (Csa), according to the Köppen climate classification. The determination of the degree of energy efficiency of the new recycled composite is essential for architects and engineers to make decisions when choosing a construction material in the building envelope. Also, the dosages of the new recycle composites according to the degree of energy efficiency of the material is interesting so that manufacturers can reproduce and market these materials.

The strategy of including recycled materials in buildings to reduce energy consumption presents great potential. It is recommended that more research is conducted focused on the characterization of new recycled materials as aggregates to optimize energy savings in buildings. In this study was focused on internal applications. For outdoor applications it is recommended to use other binders (cement and lime) so that the recycled materials could also be applied in outdoor areas because of their higher resistance to water than gypsum.

5. Conclusions

The key objective of this study was to characterize and assess the feasibility of incorporating biomass-ash into gypsum composites, following circular economy criteria. The main conclusions are:

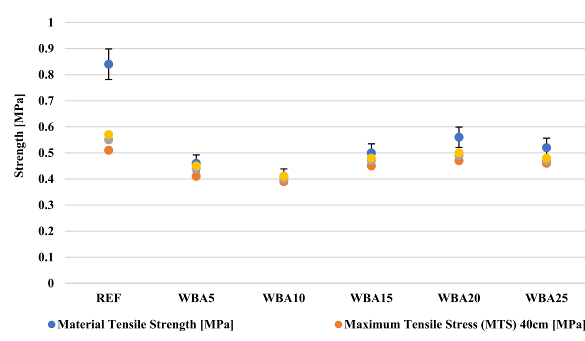

Fig. 15. Comparison of Material Tensile Strength and Maximum Tensile Stress in the tested plates with different width dimensions: 40, 60 and 120 cm.

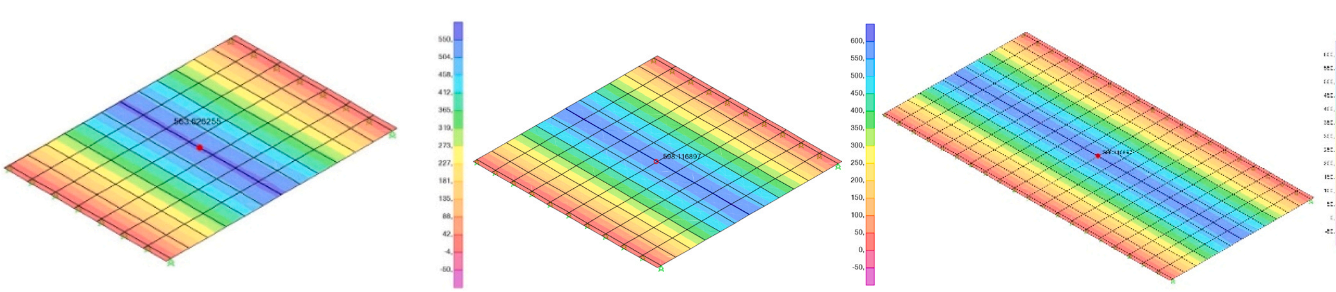

Fig. 14. Numerical finite element simulation of the bending strength test of plates with different width dimensions: 40, 60 and 120 cm.

Table 5
Characteristics of the construction system in the façade.

	Material	Bulk Density (kg/m^3)	Thermal conductivity (W/(m·K))	Thickness (m)	
				Seville	Soria
	Single-layer cement mortar	1900	1.300	0.015	0.015
	Perforated ceramic brick	900	0.500	0.115	0.015
	Cement mortar plastering	1700	1.000	0.01	0.01
	Non-ventilated air chamber	1.2	0.220	0.04	0.04
	Mineral wool	45	0.022	0.03	0.05
REF	Double hollow brick	900	0.500	0.09	0.09
REF	Gypsum plaster	988	0.300	0.015	0.015
WBA25	Plaster block + 25% WBA	1084	0.247	0.1	0.1
WBA25	Gypsum plaster + 25% WBA	1084	0.247	0.015	0.015

Table 6
Characteristics of the construction system in the flat roof.

	Material	Bulk Density (kg/m^3)	Thermal Conductivity (W/m·K)	Thickness (m)	
				Seville	Soria
	Ceramic flooring	2400	1.900	0.01	0.01
	Gripping cement mortar	1700	1.000	0.01	0.01
	Cement mortar	1700	1.000	0.03	0.03
	Extruded polystyrene (XPS)	35	0.034	0.04	0.055
	Waterproofing. Bituminous sheet	2100	0.700	0.01	0.01
	Lightened slope mortar with expanded clay	700	0.220	0.12	0.12
	Concrete slab	1110	0.938	0.30	0.30
	Non-ventilated air chamber	1.2	0.560	0.15	0.15
REF	Laminated gypsum board	988	0.300	0.015	0.015
WBA25	Laminated gypsum + 25% WBA board	1084	0.247	0.015	0.015

- Compared to the reference composite, gypsum composites incorporating biomass-ash showed similar physical and mechanical properties, which flexural and compression strength values above the norm as well as greater superficial hardness.
- Since its preliminary tests results were acceptable and it incorporated the highest percentage of waste, the best composite was the 25%-waste-containing sample.
- It was viable to use the new composites for the generation of new eco-efficient gypsum plates. Its usage means a reduction on the environmental impact of the material (up to 7.3%) and an improvement on the energy efficiency of the building (up to 5%).
- SDGs such as 8, 9, 11, 12 and 15 are positively affected by the utilization of alternative materials incorporating waste since it prolongs the life cycle of the latter and alleviates landfill waste disposal, among others.

These results indicate that while often alternative materials do in fact show promise for reducing environmental impacts of the built environment, by how much can be a challenging question to quantify and depends on a variety of factors. Nevertheless, the reutilization and valorization of biomass ash is always going to have a better environmental performance than ash landfilling.

Considering the obtained results, it can be concluded that it is feasible to incorporate biomass-ash waste into gypsum for non-load bearing applications in the construction sector, such as gypsum paste for continuous coating or prefabricated gypsum boards.

This research leaves several research lines that can be further addressed in the future, such as the performance of the compound in terms of durability, market/regulatory barriers to acceptance of materials including biomass ash, LCA analysis or the viability of recycling the new waste-containing composites.

CRediT authorship contribution statement

Flores-Colen Inês: Writing – review & editing, Supervision. **Pedreño-Rojas Manuel Alejandro:** Writing – review & editing, Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Porras-Amores César:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Villoria-Saez Paola:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Morales-Conde María Jesús:** Writing – review & editing, Writing – original draft, Validation, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

Declaration of Competing Interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Cesar Porras-Amores reports travel was provided by Government of Spain Ministry of Universities. Paola Villoria-Saez reports travel was provided by Government of Spain Ministry of Universities. Maria Jesus Morales-Conde reports travel was provided by Government of Spain Ministry of Universities. If there are other authors, they declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Table 7
Energy consumption due to the heat transfer of air renewals and through the envelope of the building located in Seville and Soria.

	Heat transfer type	Heating		Cooling		Heating + Cooling	
		Consumption (kWh)	Savings	Consumption (kWh)	Savings	Consumption (kWh)	Percentage
SEVILLE							
REF	Renovations	63,902		26,348		90,250	
WBA25	Renovations	62,762	2%	25,628	3%	88,390	2%
REF	Envelope	16,707		6889		23,596	
WBA25	Envelope	15,917	5%	6500	6%	22,417	5%
SORIA							
REF	Renovations	246,380		3139		249,519	
WBA25	Renovations	245,891	0%	2752	12%	248,643	0%
REF	Envelope	56,824		724		57,548	
WBA25	Envelope	55,194	3%	618	15%	55,812	3%

Data Availability

Data will be made available on request.

Acknowledgements

The authors would like to acknowledge the support provided by the Spanish Government aids that promote the internationalization of their researchers (José Castillejo grants codes CAS22/00320, CAS22/00341 and PRX22/00363) and Ms. Julia Mollá López for her research assistance. The author I. Flores-Colen acknowledge the support of the CERIS Research Centre (UIDB/04625/2020), and the Foundation for Science and Technology (FCT).

References

[1] ACI, 1987. Guide for structural lightweight, in: 213, A.C. (Ed.).
[2] K. Adams, M. Osmani, T. Thorpe, J. Thornback, Circular economy in construction: current awareness, challenges and enablers, Proc. Inst. Civ. Eng. - Waste Resour. Manag. 170 (2017) 15–24.
[3] AENOR, 2006. UNE EN 13279–2, Gypsum binders and gypsum plasters. Part 2: Test methods, Madrid.
[4] AENOR, 2009a. UNE-EN 13279–1, Gypsum binders and gypsum plasters. Part 1: Definitions and requirements. Spanish Association of Normalization and Certification (AENOR), Madrid.
[5] AENOR, 2009b. UNE EN 13279–1. Gypsum binders and gypsum plasters. Part 1: Definitions and requirements. Spanish Association of Normalization and Certification.
[6] AENOR, 2012. UNE-EN 12859. Gypsum blocks - Definitions, requirements and test methods. Spanish Association for Standardisation and Certification, Madrid.
[7] AENOR, 2023. UNE EN 102042 Gypsum plasters. Other test methods, Madrid.
[8] D. Alba, M. Marrero, C. Leiva, M.V. Montes, L. Vilches, Facade solutions using panels made of power plant byproducts, Inf. De. la Constr. 64 (2012) 179–190.
[9] A. Alonso, A. Rodríguez, J. Gadea, S. Gutiérrez-González, V. Calderón, Impact of plasterboard with ladle furnace slag on fire reaction and thermal behavior, Fire Technol. 55 (2019) 1733–1751.
[10] R.C. Amat, N.M. Ibrahim, N.L. Rahim, N.S.B.A. Tajudin, K.R. Ahmad, Fire resistance of biomass ash panels used for internal partitions in buildings, Procedia Eng. 53 (2013) 52–57.
[11] ASTM, 2009. D5334–08: Standard Test Method for Determination of Thermal Conductivity of Soil and Soft Rock by Thermal Needle Probe Procedure, in: Materials, A.S.f.T. (Ed.).
[12] G. Bertino, J. Kisser, J. Zeilinger, G. Langergraber, T. Fischer, D. Österreicher, Fundamentals of building deconstruction as a circular economy strategy for the reuse of construction materials, J. Appl. Sci. 11 (2021) 939.
[13] Brown, M., Haselsteiner, E., Apró, D., Kopeva, D., Luca, E., Pulkkinen, K.-L., Vula Rizvanolli, B., 2018. Sustainability, Restorative to Regenerative. An exploration in progressing a paradigm shift in built environment thinking, from sustainability to restorative sustainability and on to regenerative sustainability. COST Action RESTORE (CA16114): Working Group 1 Report: Restorative Sustainability.
[14] N.C. Cruz, F.C. Silva, L.A. Tarelho, S.M. Rodrigues, Critical review of key variables affecting potential recycling applications of ash produced at large-scale biomass combustion plants, Resour. Conserv. Recycl. 150 (2019) 104427.
[15] M. del Río Merino, J. Guijarro Rodríguez, F. Fernández Martínez, J. Santa Cruz Astorqui, Viability of using olive stones as lightweight aggregate in construction mortars, Rev. De. la Constr. 16 (2017) 431–438.
[16] EN 13279–2, 2006. Gypsum binders and gypsum plasters. Part 2: Test methods.
[17] EU, A new circular economy action plan for a cleaner and more competitive Europe (COM/2020/98), Commun. Eur. Comm. 98 (2020).
[18] Eurostat, 2023. Circular material use rate.
[19] Fořt, J., Čáchová, M., Vejmelková, E., Černý, R., 2018. Mechanical and hygric properties of lime plasters modified by biomass fly ash, IOP Conference Series: Materials Science and Engineering. IOP Publishing, p. 032059.
[20] J. Fořt, J. Šál, R. Ševčík, M. Doleželová, M. Keppert, M. Jerman, M. Záleská, V. Stehel, R. Černý, Biomass fly ash as an alternative to coal fly ash in blended cements: functional aspects, Constr. Build. Mater. 271 (2021) 121544.
[21] J. Fořt, J. Šál, J. Žák, R. Černý, Assessment of wood-based fly ash as alternative cement replacement, Sustainability 12 (2020) 9580.
[22] B.C. Guerra, S. Shahi, A. Mollaei, N. Skaf, O. Weber, F. Leite, C. Haas, Circular economy applications in the construction industry: a global scan of trends and opportunities, J. Clean. Prod. 324 (2021) 129125.
[23] INE, 2023. Instituto Nacional de Estadística (Spanish National Institute of Statistics),.
[24] ITEC, 2023. BEDEC database. Instituto Tecnológico de la Construcción (Technical Institute of Construction).
[25] A. Jiménez-Rivero, J. García-Navarro, Management of end-of-life gypsum in a circular economy. Advances in construction and demolition waste recycling, Elsevier, 2020, pp. 69–79.
[26] M. Kenward, News & analysis science policy, MRS Bull. 43 (2018) 914.
[27] H.W. Kua, S.Y.G. Choo, The use of biochar-coated lime plaster pellets for indoor carbon dioxide sequestration. Biochar from biomass and waste, Elsevier,, 2019, pp. 305–317.
[28] M. Leiva Aguilera, M. Del Rio Merino, Additived Plaster with Rice Husk Waste. Construction and building research, Springer, 2014, pp. 463–470.
[29] C. Leiva, C. Arenas, L. Vilches, B. Alonso-Fariñas, M. Rodriguez-Galán, Development of fly ash boards with thermal, acoustic and fire insulation properties, Waste Manag. 46 (2015) 298–303.
[30] C. Leiva, L.F. Vilches, J. Vale, C. Fernández-Pereira, Fire-resistance of biomass ash panels used for internal partitions in buildings, Fire Saf. J. 44 (2009) 622–628.
[31] B. Marques, A. Tadeu, J. António, J. Almeida, J. de Brito, Mechanical, thermal and acoustic behaviour of polymer-based composite materials produced with rice husk and expanded cork by-products, Constr. Build. Mater. 239 (2020) 117851.
[32] M. Morales-Segura, C. Porras-Amores, P. Villoria-Sáez, D. Caballol-Bartolomé, Characterization of gypsum composites containing cigarette butt waste for building applications, Sustainability 12 (2020) 7022.
[33] C. Porras-Amores, P. Martin Garcia, P. Villoria Sáez, M. del Rio Merino, V. Vitielo, Assessing the energy efficiency potential of recycled materials with construction and demolition waste: a spanish case study, Appl. Sci. 11 (2021) 7809.
[34] R. Rajamma, L. Senff, M. Ribeiro, J.A. Labrincha, R. Ball, G.C. Allen, V. Ferreira, Biomass fly ash effect on fresh and hardened state properties of cement based materials, J. Compos. Part B: Eng. 77 (2015) 1–9.
[35] Á. Rodríguez Sáiz, J.M. Manso, Á. Aragón, J.J. González, Strength and workability of masonry mortars manufactured with ladle furnace slag, Resour. Conserv. Recycl. 53 (2009) 645–651.
[36] J. Santa-Cruz-Astorqui, M. Del-Río-Merino, P. Villoria-Sáez, C. Porras-Amores, Analysis of the viability of prefabricated elements for partitions manufactured with plaster and EPS from waste recycling, DYNA-Ing. e Ind. 94 (2019) 415–420.
[37] Spanish Government, 2006. Real Decreto 314/2006. Código Técnico de la Edificación (Royal Decree 314/2006. Technical Building Code). Spanish government.
[38] L.F. Vilches, C. Leiva, J. Vale, J. Olivares, C. Fernandez-Pereira, Fire resistance characteristics of plates containing a high biomass– ash proportion, Ind. Eng. Chem. Res. 46 (2007) 4824–4829.
[39] P. Villoria Sáez, M. del Río Merino, E. Atanes Sánchez, J. Santa Cruz Astorqui, C. Porras-Amores, Viability of gypsum composites with addition of glass waste for applications in construction, J. Mater. Civ. Eng. 31 (2018).
[40] WEF, 2016. Shaping the future of construction a breakthrough in mindset and technology, World Economic Forum. World Economic Forum.
[41] M. Záleská, Z. Pavlík, M. Pavlíková, L. Scheinherrová, J. Pokorný, A. Trník, P. Svora, J. Fořt, O. Jankovský, Z. Suchorab, Biomass ash-based mineral admixture prepared from municipal sewage sludge and its application in cement composites, Clean. Technol. Environ. Policy 20 (2018) 159–171.