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Eco-efficient transformation of mineral wool wastes into lightweight aggregates at low firing temperature and associated environmental assessment

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ABSTRACT

Waste recycling is one of the key elements to mitigate the environmental problems that threaten our society. Mineral wool is currently the most widely used insulation material in the European Union, so the amount of waste generated in the demolition and restoration of buildings has increased alarmingly. This work investigates for the first time the use of glass wool (GW) and rock wool (RW) as a component in the manufacture of lightweight aggregates, showing that both can be suitable raw materials considering the density (1.3–1.5 g/cm^3) and mechanical strength (2–6 MPa) obtained. In addition, the use of GW would help to reduce the firing temperature significantly (700 °C) compared to that normally used in the manufacture of these materials (around 1200 °C), which would imply significant energy savings. Considering that thermal insulation materials and lightweight aggregates are among the most widely used materials in the construction sector, the work presented here also evaluates the environmental impact associated with the manufacture of lightweight aggregates with RW and GW in comparison with the traditional process, using the Life Cycle Assessment (LCA) methodology. A significant environmental improvement has been observed in almost all the analyzed impact categories of the artificial aggregates manufactured with mineral wool with respect to traditional LWAs.

1. Introduction

Since the Industrial Revolution, the European economic model has been based on the linear sequence of "extract, produce, waste". As this was reaching the limits of its environmental and economic viability, it was necessary to look for a new alternative. This new model is known as the circular economy and its basic principles include maintaining the value of resources for as long as possible and reducing the waste generated. This allows them to be reintroduced into the cycle. The new EU Waste Framework Directive 2008/98/EC [1] establishes that, by 2020, 70% of construction and demolition waste (CDW) should be reused, recycled or recovered. Mineral wool waste accounts for 0.2% of the volume of all CDW. Different studies show that this waste is increasing annually by 1.2%, and its increase is expected to continue in the coming years [2]. Although it is difficult to estimate the actual volumes of this waste, as reliable data are scarcely available, it is estimated that by 2020 it will exceed 2.5 million tons [3], which could end up in landfill.

The large amount of mineral wool, as waste, which is estimated to be generated at present, represents a challenge for society. Therefore, there are several studies on its reuse in different areas of industry, such as in the manufacture of concrete [4–6,14], mortar [7,8], wood-plastic composites [9,10], gypsum [2], ceramic foams [11] and asphalt mixtures [12–14]. Some studies have also been carried out using these wastes as precursors for alkaline activation, as they present theoretically suitable chemical and mineralogical compositions [15,16]. After consulting the literature, it was decided to pursue a line of research for the utilization of mineral wool for which there are no bibliographic precedents: the manufacture of lightweight aggregates.

According to Cheeseman et al. [17] a lightweight aggregate is considered as such, if it presents a strong porous sintered ceramic core, but of low density, a dense external surface to avoid water absorption and an almost spheroid shape to improve the workability of fresh concrete. The EN 13055–1 [18] standard states that for an aggregate to be

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considered as 'lightweight' it must have a particle density (ρ_{rd}) of less than 2000 kg/m^3 and/or a bulk density (ρ_B) of less than 1200 kg/m^3. The technological advantages offered by lightweight aggregates over conventional aggregates, together with the transition towards a circular economy, are being reflected in numerous investigations on the valorization of waste as raw materials for manufacturing. Examples are different types of solid waste, from coal-fired power plants, mining, metallurgical and agricultural industry among others [19]. No evidence has been found that mineral wool has been used for this purpose.

However, studies focused on the development of new materials should not only focus on the improvement of their technological and mechanical properties. The analysis of their environmental properties should also be a priority [19,20].

Until a little more than a decade ago, efforts to minimize environmental pollution were focused on cleaning or purifying the environment (air, water or soil) where effluents or polluting emissions were released. These types of solutions have proven ineffective since they deal with the problem once the processes have taken place, the products have been manufactured and the waste and emissions have been generated, in addition to nullifying the competitive possibilities of companies due to their high cost. Sustainability is not only linked to the research sector. Aggregates companies such as LECA, have been working for some time on the circular economy with different sustainable alternatives throughout their European centers where they incorporate local wastes for the production of aggregates. The adoption of an integrating and global perspective, throughout the entire life cycle of the product, at the time of allocating, assessing and making decisions to minimize the environmental impacts associated with it, seems the most reasonable thing to do. For this purpose, the Life Cycle Assessment methodology, defined by ISO 14040 [21], is available as a technique for evaluating the environmental aspects and potential impacts associated with a product.

Different studies on Life Cycle Assessment in the construction sector have shown that the environmental impact of building products can be significantly reduced by promoting the use of best available techniques and that eco-innovation in production plants, substituting the use of finite natural resources for waste generated in other production processes, preferably available locally, stimulating the creation of more sustainable products and encourage the generation of new business and job opportunities [22,23,24,25].

2. Materials and methods

2.1. Initial preparation of raw materials

Two types of mineral wool were used, a rock wool (RW) and a glass wool (GW), which were supplied in panel form by Saint Gobain Isover, S.L. (Azuqueca de Henares, Spain). They were cut into pieces and then, following a procedure analogous to that of other authors [11] were powdered for one hour in a Siemens® ball mill [26]. Since mineral wool alone is not a workable material, small proportions of <200-μm-milled sepiolite by-products from Tolsa plant (Vallecas, Spain) were used to improve workability and obtain a mixture that was subsequently easy to extrude and pelletize, in line with previous investigations [27]. The final formulations were denominated as GW + 20% S and RW + 20% S.

2.2. Raw material characterization

The particle size distribution of the ground raw materials was obtained by laser diffraction (Coulter® LSTM 230). The chemical composition was determined by XRF with an ARL ADVANT'XP wavelength dispersive sequential spectrometer. From the chemical composition data, two ratios were determined:

$$\frac{(K_2O + Na_2O)}{(CaO + MgO)} \quad (1)$$

$$\frac{SiO_2}{\sum Flux} \quad (2)$$

where:

$$\Sigma Flux = K_2O + Na_2O + CaO + MgO + FeO + Fe_2O_3 \quad (3)$$

Total carbon (TC) and inorganic carbon (IC) were measured using a Shimazdu® TOC-VCSH analyzer. The organic carbon (OC) was calculated by difference between TC and IC.

The liquid limit (LL) of the mixtures was determined by the Casagrande device method [28,29] and the plastic limit (PL) by thread bending [30], so the plasticity index (PI) was the difference between LL and PL. The optimum moisture content (W_{OP}) to achieve adequate workability was determined as follows [30,31]:

$$W_{OP} = \beta x PL \quad (4)$$

A β value of 1.234 was used for the mixture RW + 20% S (clayey workability) and 1.495 for the mixture GW + 20% S (silty-clay workability).

2.3. Lightweight aggregate manufacture protocol

The general LWA manufacture procedure followed is shown in Fig. 1. First, the mixtures were kneaded with the amount of distilled water corresponding to W_{OP}. After 48 h of maceration, the workable material was extruded (Nannetti® pneumatic extruder) and manually kneaded into spherical pellets of Ø 9.3 mm. After oven-drying, several 25-pellet batches were sintered for 4 min + 1 min preheating into lightweight aggregates, for which a Nannetti® TOR-R 120–14 rotary tube kiln was used. The firing temperature was defined by the material itself, being the maximum temperature at which the pellets can be fired without their surface adhering to the kiln tube or other specimens.

2.4. Lightweight aggregate characterization tests

The loss on ignition during the firing process was determined based on the weight change experienced by 25 pellets. Similarly, the bloating index (BI) was determined according to Fakhfakh et al. [32] based on the variation of diameter before and after sintering. The loose bulk density (ρ_B) was calculated based on the mass of aggregates used to fill a volume-known container. For apparent density (ρ_a), oven-dry density (ρ_{rd}) and percent of water absorption (WA_{24}), the EN 1097–6:2014 [33] standard was followed.

The percentage of total porosity (P_T) was determined as follows [34,35]:

$$P_T = \left(1 - \frac{\rho_{rd}}{2.6}\right) x100 \quad (5)$$

The open porosity (P_O) was calculated according to De Santiago-Buey and Raya García [36]:

$$P_O = \left(1 - \frac{\rho_{rd}}{\rho_a}\right) x100 \quad (6)$$

Therefore, closed porosity (P_C) is:

$$P_C = P_T - P_O \quad (7)$$

The mechanical strength of individual aggregates (S) was determined as the average value after crushing 25 specimens of each type using a Nannetti® FM 96 press, considering both the load and the diameter of each specimen [37,38].

2.5. LCA methodology

The ISO 14040:2006 standard [21] defines LCA as "a method for assessing the environmental aspects and potential impacts associated

Fig. 1. Diagram of the process followed to obtain lightweight aggregates with RW and GW.

with a product, process or activity". The ISO 14044:2006 standard [39] specifies the interrelated stages that make up an LCA, establishing first the "definition of the objective and scope". Thus, LCA has been carried out as a comparative analysis of three product: traditional lightweight aggregates made exclusively with clay (CA), lightweight aggregates made with RW + 20% sepiolite (RWA) and lightweight aggregates made with GW + 20% sepiolite (GWA) to evaluate their environmental performance, so that the material with the least impact on the environment can be defined.

The functional unit established in this study is the analysis of 1 kg of artificial lightweight aggregates with bulk density between 400 and 1200 kg/m^3 [18]. Fig. 2 shows a comparative scheme of the three scenarios compared in this work.

Fig. 3 shows the boundaries and different stages of the system studied, indicating that a "cradle-to-gate" approach has been established. In addition, a maximum radius of action of 50 km has been assumed for the transport scenario.

After defining the objective and scope, the life cycle inventory (LCI) phase must be carried out. To carry out the quantification of the input (raw materials and energy) and output (emissions and waste) flows that cross the system boundaries, it was used:

(i) data from the Ecoinvent v3 database [40];

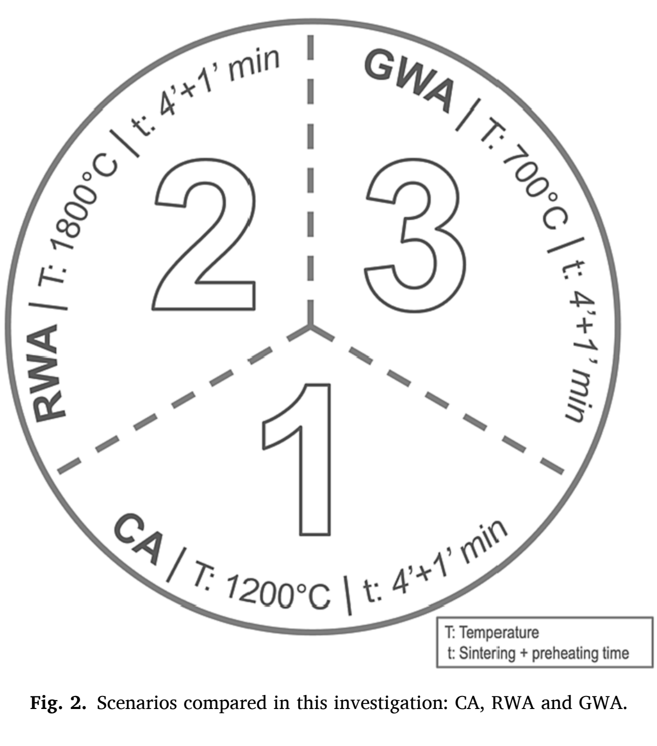

Fig. 2. Scenarios compared in this investigation: CA, RWA and GWA.

(ii) empirical measured and processed data based on experimental laboratory investigations of feedstock ratios, gas emissions and energy consumption;

(iii) data from literature sources [41,42].

The methodology used to carry out the life cycle impact assessment (LCIA), after inventory sampling, was CML 2000 v2.05. The environmental impact of the products studied was analyzed comparatively. This methodology allows a classification and evaluation of the previous inventory by relating them to observable environmental effects through the following impact categories: abiotic depletion, acidification, global warming potential, ozone layer depletion, photochemical oxidation, eutrophication, human toxicity, freshwater ecotoxicity, marine aquatic ecotoxicity and terrestrial ecotoxicity.

The SIMAPRO Life Cycle Assessment software was used to carry out the LCA. SIMAPRO is a reference tool for conducting LCA research [23,43,44]. Table 1 includes the data that make up the life cycle inventory for the present work.

3. Results and discussion

3.1. Characterization of raw materials and their mixtures

The particle size distribution in the ground raw materials indicates a large degree of fineness (Fig. 4), with mean particle sizes of 56.1, 34.0 and 18.5 μm and d_{50} values of 35.8, 21.0 and 10.9 μm in GW, RW and the added sepiolite, respectively. The carbon content of the blends comes mainly from the mineral wool, which would be linked to the resins that usually incorporate this type of material. The carbon is therefore mainly organic, reaching 5.5 wt% in GW and 2.5 wt% in RW, which translates into TC values of 4.6 and 2.2 wt%, respectively, in the final blends (Table 2).

Among the chemical composition data in Table 2, some of them are noteworthy. In the case of GW, the ratio $(K_2O + Na_2O)/(CaO + MgO)$ is higher than 1, and that of $SiO_2/\sum Flux$ higher than 2, which could be indicative of an adequate viscosity to obtain LWAs [32,45], something that is maintained when sepiolite is incorporated into the mixture. However, the absence of Al_2O_3 in GW, translates into a very low proportion of this oxide in the final mixture, which contrary to the above could impede the LWA formation [46]. In the case of RW and its mixture with clay, neither the general chemical composition nor the ratios deduced from it seem to point to a good predisposition to expansion, mainly due to a relative excess of fluxing oxides, such as CaO (21.8 %), over SiO_2 and Al_2O_3. Despite this, it will be the experimental results that will determine whether or not the raw materials are suitable, as predictive approaches based on chemical composition have been shown to have relatively high margins of imprecision [19].

Regarding the resulting mixtures, although GW and RW were non-plastic, the addition of 20 wt% sepiolite, has favored the workability of the blends to be suitable for the subsequent pelletizing stage, as shown

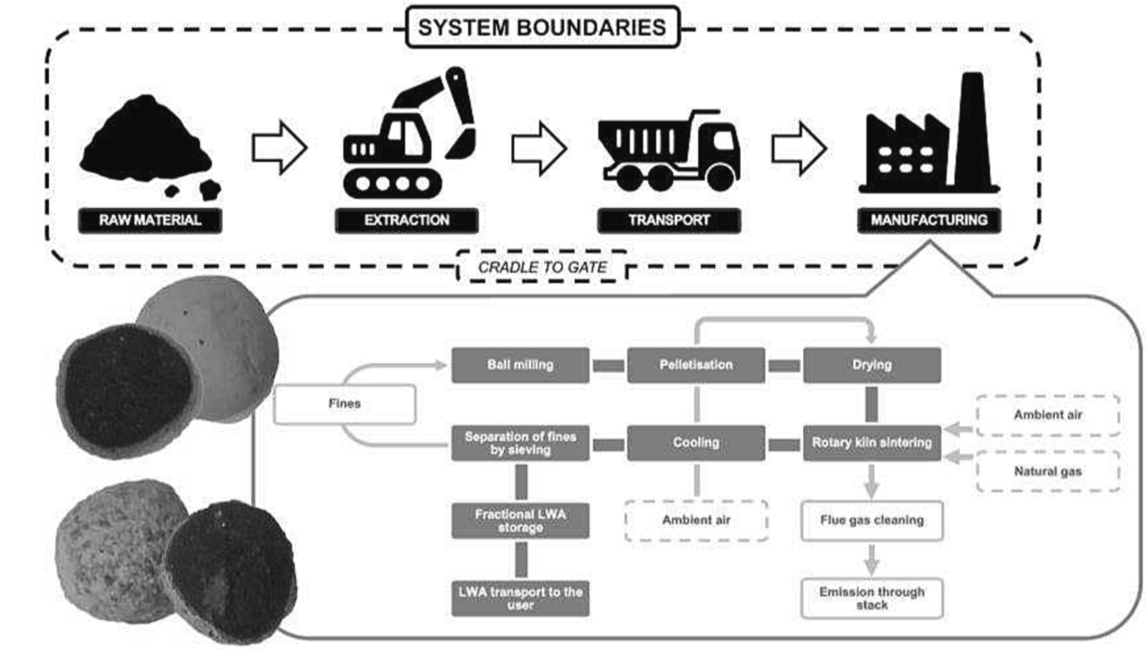

Fig. 3. Schematic of LWA production and system boundaries considered.

Table 1
Inventory data associated with the production of 1 kg of lightweight aggregates for the different phases analyzed: raw materials, extraction, transport and manufacturing.

Elementary flow	Units	CA	RWA	GWA
Raw materials				
Clay	kg	1.147	–	–
Sepiolite	kg	–	0.2251	0.2251
Stone wool	kg	–	0.64	–
Foam glass	kg	–	–	0.64
Extraction and transport				
Water	m^3	0.0134	0.0134	0.0134
Transport raw materials	tkm	0.0747	0.0747	0.0747
Diesel, burned in building machine	MJ	0.0096136	0.0096136	0.0096136
Extraction plant	p	2.00×10^{-10}	2.00×10^{-10}	2.00×10^{-10}
Energy and material inputs at LWA manufacturing plant				
Electricity	kWh	0.028881	0.028654	0.026785
Heat	MJ	2.54981	2.542026	2.386471
Packaging film	kg	0.0004813	0.0004813	0.0004813
Linerboard	kg	0.002	0.002	0.002
Emissions from thermal processing of raw materials				
Water (air)	m^3	0.0000067	0.0000067	0.0000067
Carbon dioxide (air)	m^3	0.0184	0.0039	0.0041
Sulfur dioxide (air)	m^3	–	0.0276	0.028
Water	m^3	0.0000067	0.00008568	0.00008568

by the data in Table 3. The LL data are close to or above 60 and the PI/LL ratio is around 0.5 or higher, which is indicative that the final mixtures have the typical workability of a clayey material. Once the optimum moisture content (around 40–44 %; Table 3) has been added, this has meant that the mixtures have been able to be extruded and granulated without problems.

3.2. Technological properties of the aggregates obtained

Fig. 5 shows the appearance of GWA and RWA aggregates sintered from glass wool and rock wool, respectively. As can be seen, there is a clearly differentiated colored shell and core. While the shell has a light shade (grayish in the case of RWA and yellowish in GWA), the core is practically black in both cases. This dark color would be linked to the fact that in the interior of the aggregate there have been reductive conditions that, on the one hand, would lead to the reduction of the iron present and, on the other hand, could also be linked to an incomplete decomposition of the organic matter of the original raw material [47,48].

According to Table 4, firing the aggregate with GW results in a slightly higher LOI than the aggregate with RW (8.7 % in GWA vs 6.7 % in RWA), due to the thermal decomposition of not only organic species, but also certain mineral phases that might be present (e.g. soda-ash used as flux in mineral wool, which would explain the high sodium content of GW). However, the firing temperature is much lower in GWA (700 °C) than in RWA (1180 °C). In fact, while the temperature applied in RWA would be in the common range applied in LWAs, that of GWA is abnormally low, possibly due to the presence of a high sodium content in the original sample that could favor such a decrease. The environmental advantages due to this low temperature will be discussed in the next section based on the LCA study.

From a technological perspective, although the negative bloating index suggests a slight reduction in aggregate size with respect to the original pellet, both ρ_B and ρ_{rd} indicate that the aggregates would meet the specifications for lightweight aggregates indicated in the EN-13055–1 standard [18], since the density is clearly lower than the established limits (1.20 and 2.00 g/cm^3 for ρ_B and ρ_{rd}, respectively). In the case of GWA, it is somewhat lighter than RWA (ρ_{rd} = 1.36 vs 1.51 g/cm^3). This is because the porosity generated during firing has been higher in GWA than in RWA (47.7 vs. 41.9 %), leading to lower mechanical strength (S = 3.2 MPa in GWA vs S = 8.8 MPa in RWA). The predominant type of porosity in both cases is the open type, especially in GWA (32.3 %), which means a higher water absorption in this variety of aggregate compared to RWA (WA_{24} of 24.1% vs 14.7%).

Taking this into account, depending on the final application, the use of GWA would be more justified than RWA when the objective is to reduce density or to favor good hydraulic conductivity. On the contrary, if, in addition to having low density, the objective is to have a better mechanical strength, the use of RWA would be the best option of the two

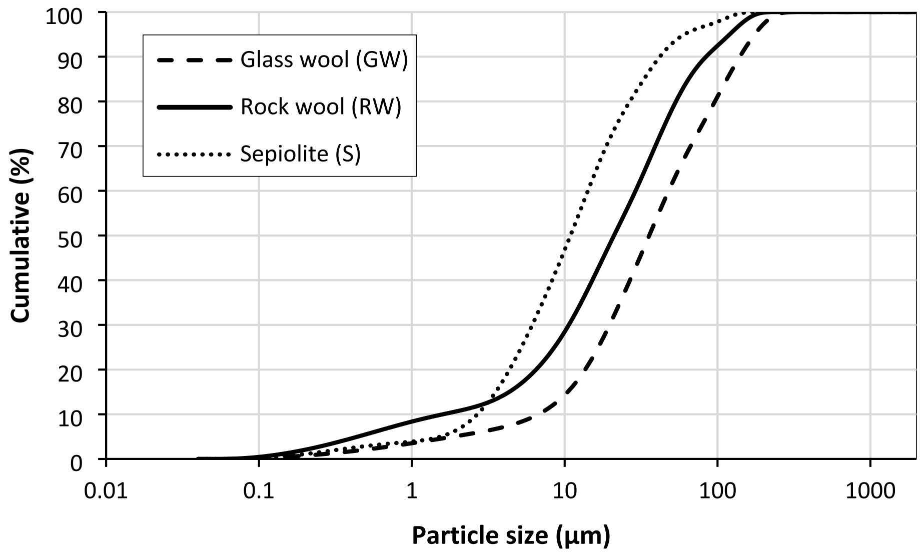

Fig. 4. Cumulative particle size distribution of the raw materials after milling.

Table 2
Chemical composition of raw materials and mixtures. GW = Glass wool; RW = Rock wool; S = Sepiolite.

Raw material or mixture	Carbon content (%)			Chemical composition (%)									Ratios	
	TC	IC	OC	SiO_2	Al_2O_3	Na_2O	CaO	MgO	Fe_2O_3	K_2O	SO_3	LOI (1000 °C)	$(K_2O + Na_2O)/(CaO + MgO)$	$SiO_2/\sum Flux$
GW	5.5	0.0	5.5	58.8	–	16.6	7.5	2.2	0.9	0.8	1.1	10.6	1.8	2.1
RW	2.5	0.0	2.5	39.4	14.4	2.3	21.8	8.3	6.4	0.9	0.4	3.9	0.1	1.0
S	0.9	0.4	0.4	54.8	7.2	0.5	2.0	21.9	2.0	1.6	–	9.8	0.1	2.0
GW + 20%S	4.6	0.1	4.5	58.0	1.4	13.4	6.4	6.1	1.1	0.9	0.9	10.4	1.1	2.1
RW + 20%S	2.2	0.1	2.1	42.4	12.9	1.9	17.8	11.0	5.5	1.1	0.3	5.1	0.1	1.1

Table 3
Results of Atterberg limits and optimum moisture content for the mixtures studied (LL: Liquid Limit; PL: Plastic Limit; PI: Plasticity Index).

Mixture	LL	PL	PI	PI/LL	W_{OP} (%)
GW + 20% S	59.8	26.6	33.2	0.56	39.8
RW + 20% S	67.8	35.4	32.4	0.48	43.7

presented, something that is also reflected in the S/ρ_{rd} ratio, which would indicate better balanced properties in RWA (5.8 N/m·g) than in GWA (2.4 N/m·g).

3.3. LCA: Contribution and influence analysis

Fig. 6 and Table 5 show the impacts associated with each of the production stages for 1 kg of traditional all-clay lightweight aggregates (CA) and 1 kg of RWA and GWA lightweight aggregates, respectively. The RWA and GWA obtained similar results to each other for all stages.

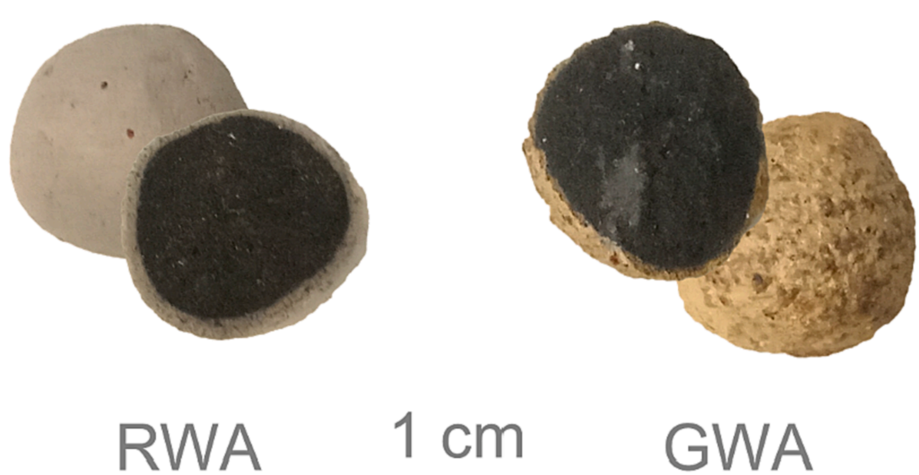

Fig. 5. Lightweight aggregates obtained from rock wool (left) and glass wool (right).

Table 4
Technological properties of the lightweight aggregates obtained in this study.

LWA	T (°C)	LOI (%)	BI (%)	Density (g/cm^3)			WA_{24} (%)	Porosity, P (%)			S (MPa)	S/ρ_{rd} (N·m/g)
				ρ_B	ρ_a	ρ_{rd}		P_T	P_O	P_C		
GWA	700	8.7	−4.2	0.81	2.01	1.36	24.1	47.7	32.3	15.4	3.2	2.4
RWA	1180	6.7	−1.3	0.86	1.94	1.51	14.7	41.9	22.2	19.8	8.8	5.8

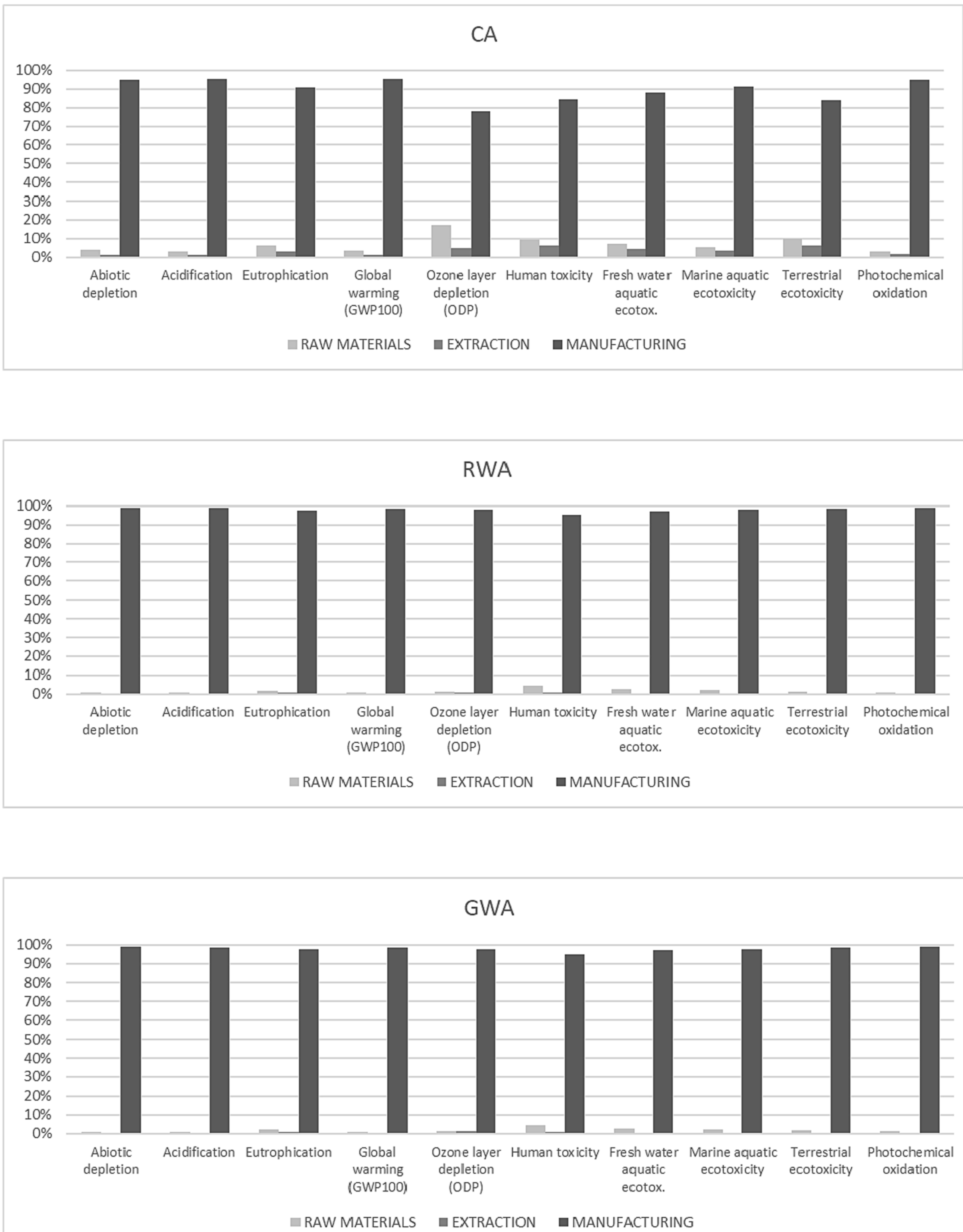

Fig. 6. Contribution of the impacts related to manufacturing 1 kg of CA, RWA and GWA at different stages.

Table 5
Impacts associated with 1 kg of CA, RWA and GWA.

Impact category	Units	CA	RWA	GWA
Abiotic depletion	kg Sb eq	0,00199051	0,00148224	0,00139401
Acidification	kg SO2 eq	0,00241016	0,00155456	0,00146094
Eutrophication	kg PO4— eq	0,00048324	0,0002933	0,00027601
Global warming (GWP100)	kg CO2 eq	0,35370129	0,2045324	0,19273846
Ozone layer depletion (ODP)	kg CFC-11 eq	9,1822E-09	1,6983E-08	1,5971E-08
Human toxicity	kg 1,4-DB eq	0,25283681	0,10976828	0,10346425
Fresh water aquatic ecotox.	kg 1,4-DB eq	0,09807098	0,05054083	0,04763282
Marine aquatic ecotoxicity	kg 1,4-DB eq	256,211578	127,221811	120,079363
Terrestrial ecotoxicity	kg 1,4-DB eq	0,00096416	0,00134161	0,00126108
Photochemical oxidation	kg C2H4 eq	0,00011231	6,7992E-05	6,3908E-05

A significant difference of both with respect to CA is observed in the manufacturing stage, due to the differences in the sintering conditions of the aggregates. Even so, the manufacturing stage maintains, in all the scenarios analyzed, contributions above the significant margin (>50%), with somewhat lower values for the categories Ozone layer depletion (78% for CA), Human toxicity (84% for CA), Terrestrial ecotoxicity (84% for CA), Fresh water aquatic ecotoxicity (88% for CA).

Regarding the impact categories, it should be noted that the Global Warning Potential of CA presents values close to 0.37–0.38 kg eq. CO_2/kg for CA as reported by other authors [49]. Within this same category, the stage with the lowest contribution to the impact is the extraction stage, which represents between 0 and 1% of the total for the three scenarios studied. Something similar occurs with the raw materials stage, with values of 1% to 3% for CO_2 emissions. Undoubtedly, the manufacturing stage is responsible for the greatest final impact, with a contribution of up to 99% (95% for CA). This is due to the long periods of time that kilns must remain at very high temperatures and the consequent economic and environmental cost that this entails, which contributes to the increased combustion of fossil fuels responsible for powering kilns at such temperatures, as reported by authors who have analyzed the ceramic sector [50,51].

The remaining nine impact categories show variations of less than 1% for RWA and GWA in the raw materials and extraction stages. One-Layer Depletion category stands out for CA where the contribution of raw materials increases up to 17%. Other authors have also found this effect [52,53]. This value is associated with the fuel consumption of extraction machinery and distribution vehicles, as well as natural gas and electricity used in atomization plants, emitters of substances such as methane, bromotrifluoro, Halon 1301, etc.

Fig. 7 shows the values of each impact category referred to a relative scale of 100%, whose maximum value represents the highest impact recorded in each of the categories analyzed. According to this comparison, of the LWAs made from waste, GWA has the lowest environmental impact for all the impact categories analyzed.

When comparing the three materials tested, GWA remains the most environmentally beneficial according to the impact categories abiotic depletion, acidification, eutrophication, global warming potential, human toxicity, freshwater ecotoxicity, marine aquatic ecotoxicity and photochemical oxidation. However, for the ozone depletion and terrestrial ecotoxicity categories, traditional LWAs show lower values than aggregates made from waste.

The normalization of the different categories allows a standardized evaluation of the impact categories with respect to the impact generated by an average European in a year [54].

The normalization of the data is shown in Table 6, where the most important impacts can be recognized according to the material and the results are very similar to those shown in Table 5.

4. Conclusions

The work presented shows how two types of mineral wool (GW and RW) are used in the manufacture of lightweight aggregates. The main conclusions that can be drawn are shown below:

- Although a priori the lack of plasticity of mineral wool could be an impediment for its pelletization, the addition of clay (in this case a 20 wt% of by-products rich in sepiolite) can facilitate the adequate workability of the final mixtures.
- The most suitable temperature for sintering was 700 °C and 1180 °C for the aggregates containing GW and RW, respectively. When compared to the temperatures normally employed in the manufacture of lightweight aggregates, the low temperatures used in the GW

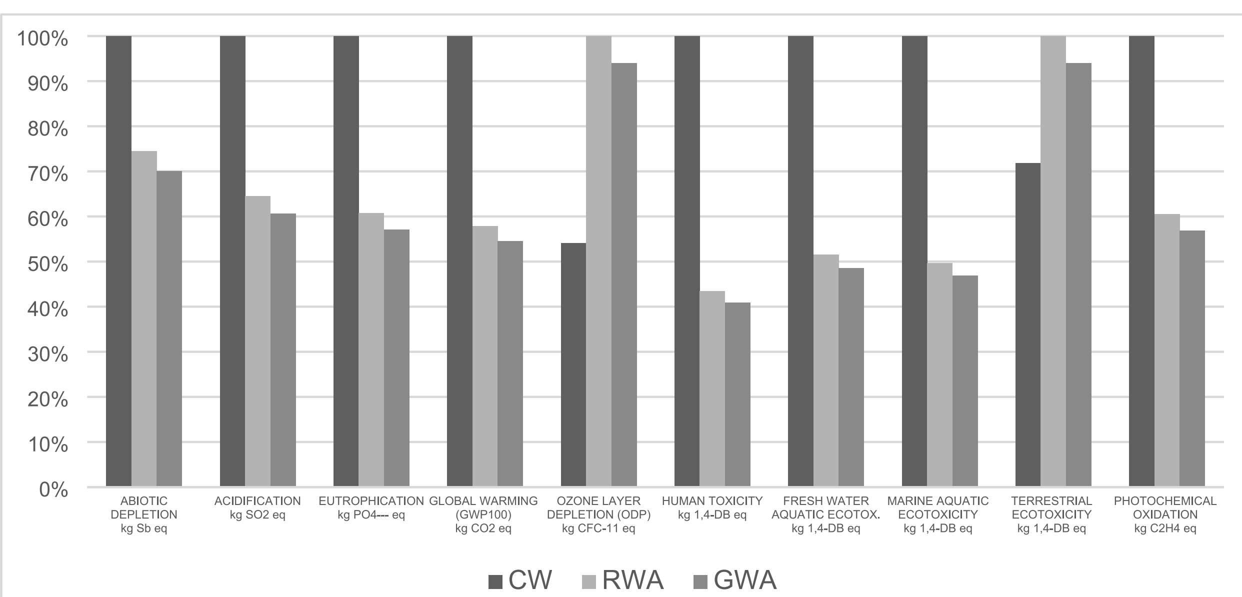

Fig. 7. Comparative environmental characterization for CA, RWA and GWA.

Table 6
Normalized impacts associated with 1 kg CA, RWA, GWA, respectively.

Impact Categories	Units	Expanded clay			RW + 20%S			GW + 20%S		
		Raw materials	Extraction and transport	Manufacturing	Raw materials	Extraction and transport	Manufacturing	Raw materials	Extraction and transport	Manufacturing
Abiotic Depletion	kg Sb eq	4.49363×10^{-14}	1.65791×10^{-14}	1.10293×10^{-12}	6.36704×10^{-15}	3.55948×10^{-15}	8.57183×10^{-13}	6.34176×10^{-15}	3.55948×10^{-15}	8.05596×10^{-13}
Acidification	kg SO_2 eq	1.14175×10^{-13}	5.00877×10^{-14}	3.42687×10^{-12}	1.88353×10^{-14}	9.95276×10^{-15}	2.28751×10^{-12}	1.87605×10^{-14}	9.95276×10^{-15}	2.14809×10^{-12}
Eutrophication	kg PO_4^{3-} eq	5.79898×10^{-14}	3.12713×10^{-14}	8.72391×10^{-13}	1.02963×10^{-14}	3.07188×10^{-15}	5.70303×10^{-13}	1.02554×10^{-14}	3.07188×10^{-15}	5.35924×10^{-13}
Global Warming Potential	kg CO_2 eq	4.68291×10^{-14}	1.87413×10^{-14}	1.33509×10^{-12}	6.95481×10^{-15}	3.51382×10^{-15}	7.9948×10^{-13}	6.92719×10^{-15}	3.51382×10^{-15}	7.52803×10^{-13}
One-Layer Depletion	kg CFC-11 eq	1.60234×10^{-15}	4.42216×10^{-16}	7.32124×10^{-15}	2.01408×10^{-16}	1.62647×10^{-16}	1.69585×10^{-14}	2.00608×10^{-16}	1.62647×10^{-16}	1.59271×10^{-14}
Human Toxicity	kg 1.4-DB eq	1.29642×10^{-13}	8.18272×10^{-14}	1.13362×10^{-12}	2.46457×10^{-14}	3.22596×10^{-15}	5.56096×10^{-13}	2.45477×10^{-14}	3.22596×10^{-15}	5.22656×10^{-13}
Fresh Water Aquatic Ecotox	kg 1.4-DB eq	9.27434×10^{-13}	6.04084×10^{-13}	1.15119×10^{-11}	1.74205×10^{-13}	6.65795×10^{-15}	6.54107×10^{-12}	1.73513×10^{-13}	6.65795×10^{-15}	6.15499×10^{-12}
Marine Aquatic Ecotoxicity	kg 1.4-DB eq	4.26833×10^{-12}	2.77088×10^{-12}	7.34112×10^{-11}	8.00183×10^{-13}	3.34563×10^{-14}	3.9114×10^{-11}	7.97004×10^{-13}	3.34563×10^{-14}	3.68745×10^{-11}
Terrestrial Ecotoxicity	kg 1.4-DB eq	1.03247×10^{-13}	6.63581×10^{-14}	8.81329×10^{-13}	1.91791×10^{-14}	7.86292×10^{-16}	1.44239×10^{-12}	1.9103×10^{-14}	7.86292×10^{-16}	1.35469×10^{-12}
Photochemical Oxidation	kg C_2H_4 eq	1.99475×10^{-14}	1.03879×10^{-14}	5.86223×10^{-13}	3.38934×10^{-15}	9.56274×10^{-16}	3.6893×10^{-13}	3.37587×10^{-15}	9.56274×10^{-16}	3.46523×10^{-13}

mixture would result in significant energy and economic savings associated with lower fuel consumption, which in turn would imply a smaller environmental footprint in the manufacturing process.

- Regarding the technological properties, the LWAs obtained from glass wool and rock wool presented characteristics analogous to those of commercial lightweight aggregates in terms of density, porosity, water absorption capacity and mechanical strength, making mineral wool waste a potentially usable resource in the manufacture of this kind of materials.
- Since LCA helps to understand and identify significant factors that can promote waste applications for the manufacture of building materials, it has been shown that the incorporation of GW and RW as a major component in the manufacture of lightweight aggregates represents an improvement in almost all environmental categories compared to traditional aggregate (no waste). Glass wool proved to be the option with the least impact on the environment, with reductions close to 60% in the most pronounced cases.

In short, the tests carried out for the characterization of lightweight aggregates suggest that mineral wool is associated with a cleaner production of these, as well as implying a reduction of this waste in landfills.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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