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Assessing the Energy Efficiency Potential of Recycled Materials with Construction and Demolition Waste: A Spanish Case Study

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Abstract: Buildings are responsible for 40% of the overall final energy consumption in the European Union. On the other hand, the construction, energy, and industry sectors generate around 50% of the waste produced in Europe, out of which a third part is construction and demolition waste (CDW). In recent years, many research works have been carried out to analyze the viability of incorporating waste, especially CDW, as a substitute for traditional raw materials with great environmental impact. However, most of the studies found cover only the mechanical characterization of the compound, and there are very few that analyze these materials in specific building applications. This research work evaluates the energy efficiency potential of recycled materials with CDW. After an exhaustive analysis of the main existing recycled materials, an energetic evaluation of several construction solutions is carried out, as well as a comparison with traditional solutions. The findings show that the incorporation of recycled materials in several building construction elements is a success, since it not only reduces the consumption of raw materials, but also reduces the energy consumption of the building. Energy savings using recycled materials can range from 8% in a warm region (such as Seville) up to 13% in cold regions (such as Soria), which are greater in heating than in cooling.

Keywords: energy efficiency; sustainable material; waste additions; cement; mortar; gypsum

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1. Introduction

Residential and service buildings, shops, offices, and equipment are responsible for 40% of the total final energy consumption in the European Union. In Spain, this percentage is lower (27.70%) because the climatic conditions are generally milder in central and northern Europe. Despite this, the overall impact is still important and it is necessary to take actions to reduce the environmental impact of buildings [1]. This issue, together with the growing interest in sustainable development and efficient use in the building sector, has led, in Spain, to the design of a series of legal measures derived from the transposition of the EU Directive 2002/91/EC on energy efficiency of buildings [2–4]. Specifically, the Royal Decree on Energy Certification (RD235/2013) obliges existing buildings, which are sold or rented, to have an energy efficiency certificate. The requirement of an energy certificate is undoubtedly driving the market towards new ways of construction, using materials and systems to improve the energy efficiency of buildings [4].

Taking into account the regulation and the serious crisis that affects the construction industry in our country, for more than six years, the sector has been changing its paradigm and looking at rehabilitation, specifically the work to improve energy efficiency, as a new model that makes the sector more sustainable. In this sense, at the National Environmental

Congress the experts came to the conclusion that it is necessary to rehabilitate around 400,000 homes a year to achieve the goal of energy efficiency [5].

On the other hand, the construction, energy, and industry sectors generate around 50% of the waste produced in Europe, and specifically construction and demolition waste (CDW) represents 33% of the waste generated in the EU [6]. For this reason, the EU has considered the CDW flow a priority stream of action. In fact, during the last decade, intense activity in the field of construction in Europe generated around 827 million tonnes of CDW on average per year and only 50% of them were recovered [7]. his situation has led governments and local administrators to promote a series of measures to recover and manage CDW, such as the Royal Decree 105/2008, which requires the selection and recovery of some types of CDW that exceed a series of amounts [8].

In this sense, numerous studies have been carried out focusing on the development of new sustainable materials that incorporate waste, in order to improve their physical, mechanical, or chemical properties, and thus be able to use them in various applications. Regarding the incorporation of waste in gypsums and plasters, there are studies that analyze the incorporation of paper waste [9], cork [10,11], textile fibers [12], wood [13], rice husk [14], sawdust [15], straw fibers [16], palm fibers [17], hemp fibers [18], graphite [19], leather [20], ceramic [12,21] gypsum plaster [22], mineral fibers [23], and plastics [24–28]. Regarding the incorporation of recycled materials into cement or lime mortars, there are studies that analyze the addition of waste from polymeric fibers [29,30], recycled aggregates [31], ceramic [32,33], mineral wool [34–37], textile fibers [38], animal fibers [39], glass fibers [40–42], recycled cellulose [43,44], and vegetable fibers [45,46]. In addition to the possible technical benefits that a certain waste can provide to the traditional material (plaster, lime, or cement), the replacement of traditional material by recycled material represents energy and economic savings because of the reduction in the amount of raw material.

Sometimes, these studies of new sustainable materials seek to improve the thermal behavior of traditional materials in order to improve the thermal efficiency of buildings. Table 1 shows several studies focused on the development of recycled materials with improved thermal performance. Some of these studies show very good thermal insulation behavior, especially those using polymers.

Finally, it is estimated that not recycling or reusing waste can lead to an increase in the use of new raw materials of around 20% of the total value of the materials used [47]. Therefore, the possibility of recovering and recycling them as alternative materials to produce construction materials represents an interesting alternative. In recent years, many research works have been carried out with the aim of analyzing the viability of using waste, especially CDW, as a substitute for traditional raw material with great environmental impact. However, most of the works found cover only the mechanical characterization of the compound, and very few studies analyze the results of these materials in a specific application in a building, which will allow the agents involved in construction to have the necessary guarantee for their prescription.

This article includes the energy evaluation of several construction solutions designed using recycled materials and compares the energy performance of these solutions with traditional solutions, in order to quantify the energy efficiency potential of recycled materials.

Table 1. Previous studies of recycled materials and their thermal characterization.

Year, Reference	Waste	Binder	Application	Thermal Conductivity [w/mK] (% of Waste Addition)	Compressive Strength [Mpa] (% of Waste Addition)
2015, [48]	Wheat and barley straw	Gypsum, cement, soil	Bricks	0.31 (3% wheat straw) 0.314 (3% barley straw)	-
2017, [49]	Rubber	Cement	Masonry units	0.8 (20% waste) 0.65 (37% waste)	15.4 (20% rubber) 6.7 (37% rubber)
2018, [50]	Sugarcane Bagasse Ash Rice Husk Ash	Clay	Bricks	0.35 (15% SBA) 0.37 (15% RHA)	5.01 (15% SBA) 5.53 (15% RHA)
2018, [51]	Glass	Clay	Bricks	0.59 (25% waste)	12.56 (25% glass)
2018, [52,53]	Expanded polystyrene Extruded polystyrene	Gypsum	Plasters, coatings	0.23 (2% EPS) 0.29 (2% XPS)	2.74 (2% EPS) 5.59 (2% XPS)
2019, [54]	Expanded polystyrene Extruded polystyrene	Gypsum	Plasterboard	0.16 (3% EPS + 1% XPS) 0.15 (2% EPS + 3% XPS)	3.56 (3% EPS + 1% XPS) 3.28 (2% EPS + 3% XPS)
2019, [55]	Glass	Gypsum	Coatings, prefabricated elements	0.28 (70% waste) 0.31 (100% waste)	8.7 (70% waste) 10.2 (100% waste)
2019 [56]	Expanded polystyrene	Gypsum	Plasterboard	0.3 (2% EPS)	2.35 (2% EPS)
2020, [57]	Chicken feathers	Gypsum	Plasterboard	0.309 (5% waste)	-
2020, [58]	Ceramics Expanded polystyrene	Gypsum	Blocks	0.28 (75% CER + 2/3 EPS)	0.95 (75% CER + 2/3 EPS)
2021, [59]	Granular cork	Cement	Non-load carrying elements	0.38 (100% waste, m3) 0.15 (300% waste, m3 + 3% slag)	-

2. Methods

This article includes the energy evaluation of the construction solutions designed, as well as a comparison with traditional solutions. The methodology followed, to energetically evaluate the constructive solutions and compare them with the traditional ones, was as follows:

- Identification of the most common construction model in Spain;
- Characteristics of the reference building;
- Characteristics of the energy simulation model;
- Selection of recycled materials and building applications.

2.1. Identification of the Most Common Construction Model in Spain

To identify the most representative construction model, it is necessary to perform an analysis of the published statistical data. To achieve this, the population and housing census of the National Statistics Institute (INE, Madrid, Spain) was analyzed first. However, the information provided was found to be insufficient, as there are no data related to the characteristics or construction systems of the current housing stock in Spain [60].

For this reason, information from the 2018 Statistical Yearbook [61] and the Building Construction Statistics report 2015–2019 was used [62]. Both documents, edited by the Ministry of Development, offer data based on the municipal licenses granted and compile the most relevant statistical information on the construction activity dedicated to building, in the modalities of: newly built construction, renovation, and total or partial demolition of buildings, and of the evolution and characteristics of the building stock at a national level.

These documents do not have the deficiencies mentioned above and allows to know the mostly used construction models.

The percentages shown below were obtained with statistical tables referring to the years 2015 to 2019 [61]. The collected data show that newly built construction works are greater than those of rehabilitation or demolition works. In addition, among the newly constructed buildings, it is observed that residential buildings represent 80% compared to 20% of non-residential buildings. Therefore, it is justified to focus the energy analysis on a new residential building. In general, newly built multi-story buildings for residential use have an average surface area of around 110 m^2. Regarding the number of floors above and below ground, the statistics show that there is a higher percentage of buildings built with four or more floors above ground (56%) and with none or one floor underground (66%).

The following percentages were obtained, with the statistical tables referring to the year 2019, of new buildings for residential use [62]. In the most relevant construction characteristics for new homes and residential use, the data are classified according to the following elements: structure (vertical/horizontal), roof (flat/inclined), enclosure, and exterior carpentry. It can be stated that the most common vertical structure is reinforced concrete (87%) and the horizontal structure consists of unidirectional slabs. As for the roofs, the flat ones are more used (81%), however, this is one of the characteristics that depends on the region. Continuous cladding predominates as exterior cladding (42%). Exterior carpentry is made of aluminum in 73% of the cases. When analyzing data on indoor air conditioning installations, 15% of residential buildings include heating, while 11% include cooling systems. Regarding the interior finishing, it is observed that the mostly used laid flooring is ceramic (57%) followed by wood (34%). Most houses have a false ceiling (92%).

From the information collected above, the general characteristics of the reference building were defined:

- New building for residential use;
- Average surface per home of 110 m^2;
- Four floors above ground level and none below ground level;
- Vertical structure of reinforced concrete and horizontal structure with unidirectional slab;
- Flat roof, exterior cladding with continuous cladding, and interior ceramic flooring;
- False ceiling;
- Cooling and heating system.

2.2. Characteristics of the Reference Building (Case 1)

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). Considering the objectives of the study, the geometry of the building has been considerably simplified, obviating the spaces dedicated to commercial premises, basements, boiler rooms, or storage rooms. Likewise, each house is considered to have constant environmental conditions, so it was not necessary to draw interior partitions or doors. Figure 1 shows the reference building, as well as the distribution of the houses on each floor.

Next, the construction systems and materials of the reference building envelope are defined following the current Spanish construction code [3] and the usual construction model in Spain. One of the most important points for the thermal characterization of the building envelope to be well defined is to know its thermal transmittance (U-value).

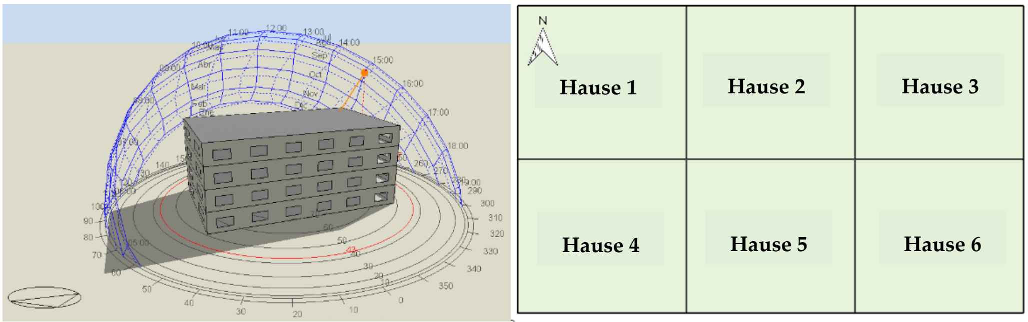

Figure 1. Distribution of reference building and housing.

Tables 2 and 3 include the type of material used for each part of the enclosure in contact with the outside: façade, basement, and flat walkable roof. The characteristics of the materials (thickness, density and thermal conductivity) have been obtained according to information published by the Eduardo Torroja Institute of Construction Sciences, CEPCO, and AICIA [63]. In cases where the layer of a construction element has a variable thickness (e.g., concrete with a slope on the flat roof), an average thickness has been considered in the simulation model. The building was located and simulated in a cold climate (Soria) and a warm climate (Seville). With these two cities, we cover a large part of the different climates of Spain.

Table 2. Characteristics of the construction system in the facade enclosure.

		SEVILLA U-Value: 0.54 W/m^{2}K		SORIA U-Value: 0.36 W/m^{2}K	
Material	**Thickness (m)**	**Density (kg/m^3)**	**Conductivity (W/m·K)**	**Density (kg/m^3)**	**Conductivity (W/m·K)**
Single-layer cement mortar	0.015	1900	1.3	1900	1.3
Perforated ceramic brick	0.115	900	0.5	900	0.5
Cement mortar plastering	0.01	1700	1	1700	1
Non-ventilated air chamber	0.04	1.2	0.22	1.2	0.22
Mineral wool	0.03/0.05	45	0.022	45	0.022
Laminated gypsum board	0.015	900	0.25	900	0.25

Table 3. Characteristics of the construction system in the flat roof.

		SEVILLA U-Value: 0.41 W/m^{2}K		SORIA U-Value: 0.34 W/m^{2}K	
Material	**Thickness (m)**	**Density (kg/m^3)**	**Conductivity (W/m·K)**	**Density (kg/m^3)**	**Conductivity (W/m·K)**
Ceramic flooring	0.01	2400	1.900	2400	1.900
Gripping cement mortar	0.01	1700	1.000	1700	1.000
Cement mortar	0.03	1700	1.000	1700	1.000
Extruded polystyrene (XPS)	0.04/0.055	35	0.034	35	0.034
Waterproofing. Bituminous sheet	0.01	2100	0.700	2100	0.700
Lightened slope mortar with expanded clay	0.12	700	0.220	700	0.220
Unidirectional concrete slab	0.30	1110	0.9375	1110	0.9375
Non-ventilated air chamber	0.15	1.2	0.560	1.2	0.560
Laminated gypsum board	0.015	900	0.250	900	0.250

Tables 2 and 3 detail the materials used in the façade and roof cladding of the reference building, together with the necessary data for the simulations (thickness, density and conductivity). The material corresponding to each enclosure to be changed in subsequent simulations is highlighted in green to compare the results obtained. No changes were made in the basement in contact with the ground, but since its transmittance is important because it affects the values obtained in the simulations, it is important to mention its composition. This will be made up of the following layers: ceramic flooring, cement mortar, extruded polystyrene, unidirectional slab, and ventilated air chamber. The transmittances obtained are 0.75 W/m^{2}K in Seville and 0.61 W/m^{2}K in Soria.

The thermal transmittance of the building envelope construction systems of the reference building meets the regulatory requirements established in the Technical Building Code [3] where the following maximum values of the characteristic parameters of the thermal envelope are set for the pre-sizing of constructive solutions in residential use: Seville (facade 0.56 W/m^{2}K; floor 0.75 W/m^{2}K; roof 0.44 W/m^{2}K) and Soria (facade 0.41 W/m^{2}K; floor 0.65 W/m^{2}K; roof 0.35 W/m^{2}K).

The gaps in the façade have a thermal transmittance (U-value) of 2 W/m^{2}K in the building located in Seville, meeting the value established in the CTE (2.3 W/m^{2}K) and 1.7 W/m^{2}K in the building located in Soria, thus fulfilling the value established in the CTE (1.8 W/m^{2}K), while for the g, the solar factor, is 0.7. This solar factor corresponds to the energy absorbed by the glass plus the energy that passes through the window, that is, the transmissivity plus the absorptivity.

2.3. Characteristics of the Energy Simulation Model

The energy simulation program EnergyPlus™ (Washington, DC, USA) is the official building simulation tool of the United States Department of Energy [64] and is widely used by the international research community to model heating, cooling, ventilation, and lighting [65–67]. The main drawback of EnergyPlus™ is the non-user-friendly graphical interface, which sometimes limits its use to experienced professionals with high specific knowledge of the tool. In this sense, DesignBuilder™ (Stroud, UK) is the most established and advanced user interface to EnergyPlus™, the industry standard building energy simulation tool [68]. Therefore, in order to simplify the modeling process, this research has been carried out with DesignBuiler™, making it possible to easily make adjustments to the building to be modeled.

To estimate the heating and cooling demand of the building, the program's climate database includes all the necessary variables. Solar radiation gains from the building are produced across all four building facades, as there are no adjoining buildings that cast shadows on the building. Similarly, shading constructive elements (e.g., parasols) have not been considered to reduce solar gains. Climate control (HVAC) is modeled on an "ideal" system that supplies the power and ventilation cables necessary to maintain comfort in the building. This means that the systems operate considering that they have an unlimited capacity, managing to satisfy any demand for cooling or heating, as well as maintaining the setpoint temperatures. This systematic approach offers the possibility to evaluate the energy efficiency of different envelope strategies in a simple way.

Specifically, the cooling system uses electricity as fuel. The system operates only between June and September. During this period, the 7–15 h system does not work, from 15–23 h it works with a set temperature of 25 °C and from 23–7 h it works with a set temperature of 27 °C. Regarding the heating system, the fuel is natural gas. The space is considered heated by an air system and is controlled based on the heating temperature setpoint. The system operates all year round except for the months of June to September. The system, from 23–7 h, works with a set temperature of 20 °C and from 7–23 h it works with a set temperature of 17 °C.

Mechanical ventilation is modeled independently of the main HVAC system. The system maintains a constant air rate of 0.63 renew/h throughout the year, except for the months of June to September. In these months the system only renews the air from 8–24 h. On the other hand, natural ventilation maintains an air rate of 4 renov/h from 24–8 h because the windows remain open at night. The infiltration flows are calculated from the value entered for the entire building, using the equations described in the EN 12,831 standard and taking into account the exposed surfaces in each area, the height of the building, the level of exposure to wind, and the infiltration units selected in the model options.

2.4. Selection of Sustainable Materials

Once the characteristics of the reference building and the simulation model have been defined, the next step is to select the most suitable recycled materials to replace some of the traditional materials defined in the previous section. This section defines the necessary characteristics of the recycled materials used to perform the energy simulations. On the one hand, several recycled materials characterized thermally by other authors have been used, and on the other hand, experimental tests have been developed to thermally characterize a recycled cement mortar, clay, and XPS waste. The six recycled materials chosen have been selected based on three criteria: (1) ease of application in the construction systems of the reference building; (2) the ease of substitution for traditional materials; and (3) their thermal insulating capacity based on the conductivity coefficient.

The experimental thermal characterization tests performed in this study have been carried out with a thermal conductivity analyzer (Model C-Therm TCi, Fredericton, NB, Canada) that allows determining the effusiveness and thermal conductivity of the material by means of a modified transient plane source method. The equipment can carry out measurements from 0 to 100 W/mK, effusivities (0–38,000 $W\sqrt{s}/m^2K$) in a wide range of temperatures (−50 to 200 °C) with an accuracy of around 5% in temperatures between 0 °C and 50 °C.

The TCI operating principle is based on experimentally determining the value of thermal effusivity by means of a sensor that presents heat reflectance on one side, interfacial and with a well-known area. The sensor induces, through electrical resistance, a constant and momentary source of heat on the sample, which varies with time. The variation in temperature with time is related to the effusivity of the sensor (known through calibration) and of the sample, which allows its determination. The test was carried out according to the C-Therm TCi Operator Manual la user [69]. Validation of the testing was carried out with the help of a reference sample of known conductivity (Pyrex-borosilicate glass), the rest of the details can be checked in a previous research work performed by the authors [70]. Table 4 summarizes the recycled materials selected.

Table 4. Recycled materials selected for the simulations phase.

Year, Reference	Waste	Binder	Application	Thermal Conductivity [w/mK]
2018, [50]	Sugarcane bagasse ash (SBA) Rice husk ash (RHA)	Clay	Bricks	0.35 (15% SBA) 0.37 (15% RHA)
2019, [54]	Expanded polystyrene (EPS) Extruded Polystyrene (XPS)	Gypsum	Plasterboard	0.15 (2% EPS + 3% XPS)
2020, [58]	Ceramics (CER) Expanded polystyrene (EPS)	Gypsum	Blocks	0.28 (75% CER + 2/3 EPS)
2021, [59]	Granular cork	Cement	Non-load carrying elements and insulation elements	0.38 (100% waste, m^3) 0.15 (300% waste, m^3 + 3% slag)
Own testing	Extruded Polystyrene (XPS)	Cement and expanded clay (EC)	Slope mortar	0.04 (50% EC + 50% XPS)

2.5. Case Studies

Once the characteristics of the reference building were defined, the simulation model and the recycled materials were selected, a series of case studies are set in which some traditional materials are replaced by recycled materials. The objective is to evaluate the potential of recycled materials to improve the energy efficiency of buildings. The overall energy behavior of the building will largely depend on the thermal properties of the materials of its envelope. Table 5 summarizes the recycled materials that will be incorporated into the façade and roof of the building, as well as the traditional material for which it is substituted. In addition, the thermal resistance values used in the simulation models are included. The thicknesses used are the same as those described in Tables 2 and 4.

Table 5. Traditional materials replaced by recycled materials in the case studies analyzed.

Building System	Application	Recycled Material		Traditional Material	
		Material	Thermal Resistance [m^{2}K/W]	Material	Thermal Resistance [m^{2}K/W]
Façade	Outer coating-Monolayer	Cement mortar with granular cork waste and slag	0.10	Cement mortar	0.01
Façade	Exterior Brick Wall	Ceramic brick with sugarcane bagasse ash (SBA)	0.33	Perforated ceramic brick	0.23
Façade	Coating and Plastering	Cement mortar with granular cork waste and slag	0.07	Cement mortar	0.01
Facade	Interior cladding-Plasterboard	Plaster with expanded polystyrene	0.10	Laminated gypsum board	0.06
Roof	Basement	Cement mortar with granular cork waste and slag	0.20	Cement mortar	0.03
Roof	Lightened mortar slope formation	Cement mortar with arlite and extruded polystyrene	3.00	Lightened slope mortar with expanded clay	0.55
Roof	False ceiling-Plasterboard	Plaster with expanded polystyrene	0.10	Laminated gypsum board	0.06

In total, eight simulations were carried out. The four simulations carried out in each of the mentioned locations (Seville and Soria) correspond to the following scenarios:

- CASE 1 (reference case). Roof and façade with traditional materials (Tables 2 and 3);
- CASE 2. Roof with traditional materials (Table 3) and façade incorporating recycled materials (Table 5);
- CASE 3. Roof that incorporates recycled materials (Table 5) and façade with traditional materials (Table 2);
- CASE 4. Roof and façade incorporating recycled materials (Table 5).

3. Results

3.1. Consumption of the Reference Building with Traditional Materials

This section analyzes the energy losses in the reference building at both locations, as well as the potential for improvement in energy savings. In absolute terms, the energy expenditure due to heating is 30,819.60 kWh (11.68 kWh/m^2), which is higher than the cooling expenditure of 12,630.92 kWh (4.79 kWh/m^2) in Seville; while, in Soria, the losses due to heating are 115,076.95 kWh (43.96 kWh/m^2), higher than the cooling cost of 1453.99 (0.55 kWh/m^2). The consumptions obtained are low because it is a new building that complies with all the energy and construction requirements established in the regulations.

Consumption due to air conditioning (cold and heat) may be due to the transfer of heat by transmission through the enclosure or to changes in air. In this research, the improvement in the energy efficiency of the building is only limited to reducing heat transfer by transmission in the envelope using new materials designed from construction waste. That is why the first step is to know the percentage of energy losses in both cities due to air renewals or heat transfer through the envelope.

In Sevilla, the assumption that there was no heat transmission through the building envelope meant that there would always be losses due to air renewals (72%) compared to losses due to heat transfer (28%). For this reason, the energy savings of the building due to air conditioning (cold and heat) is limited to 44% of the total cost. Regarding the behavior of the building depending on the time of year, in the cold months, where the highest consumption of the building occurs, heating consumption is mainly due to energy losses due to air renewals of the ventilation system and infiltrations of air. On the other hand, in hot months, cooling consumption is due to energy gains due to heat transfer through the building envelope. In addition, the energy losses occur in the same way in the glazing, walls and floor, being around 27% and 28%, while, in the roof, the losses are reduced reaching 18%.

On the other hand, in Soria, the results show that under the assumption that there was no heat transfer through the building envelope, there would always be losses due to air renewals (78%) compared to 22% losses due to heat transfer. Therefore, the energy savings of the building due to air conditioning (cold and heat) is limited to 20% of the total cost. Regarding the behavior of the building depending on the time of year, in the cold months where the building's highest consumption occurs, heating consumption is due again to energy losses due to air renewals in the ventilation system and air infiltrations. On the other hand, in hot months, cooling consumption is due to energy gains due to heat transfer through the building envelope. Energy losses occur mainly through the glazing (36%) while in the roof and façade walls (21% and 30%, respectively) the impact is more moderate, dropping considerably on the ground (13%).

At present, the implementation of recycled materials from the work for the manufacture of glazing surfaces is complex, and there are no previous studies on the matter. In addition, this research focuses on the application of new materials based on plaster or cement, so its application is limited to the blind part of the envelope. For this reason, the glazing is not considered in the analysis of the results. Despite the above, the potential for improvement continues to be considerable, since the roof, the façade walls, and the basement represent 73% in Seville and 64% in Soria of heat losses due to the envelope.

Another interesting aspect is the behavior of the temporal evolution of heat transmission through the envelope. Figures 2 and 3 show the energy losses-gains by conduction heat transfer (envelope) throughout the year in Sevilla and Soria, respectively. Heat transfer values have been normalized in relation to the constructed floor area (Wh/m^2) to make comparisons with other studies.

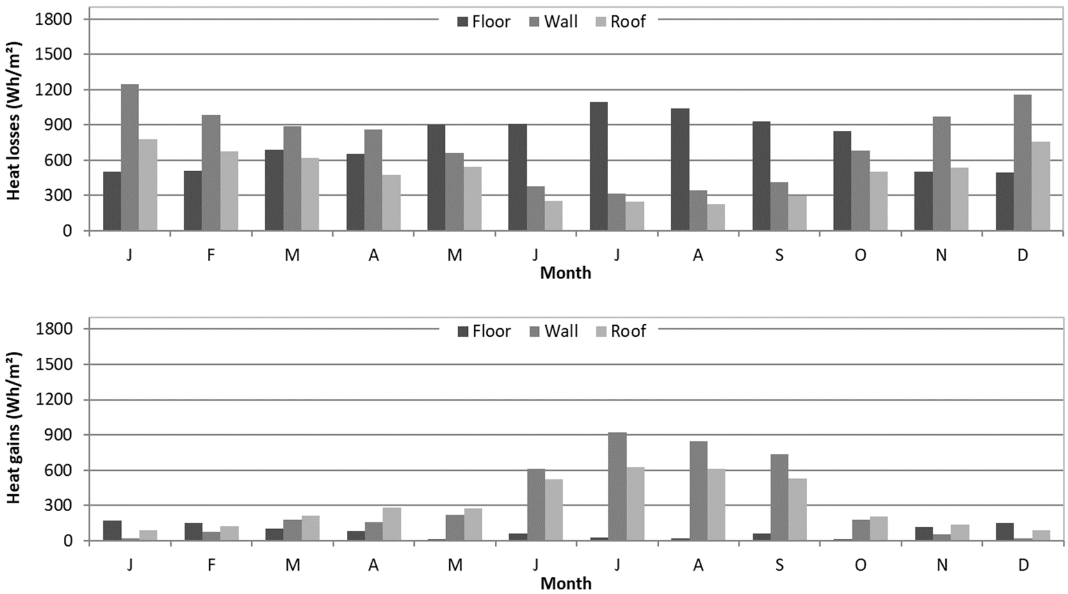

Figure 2. Energy losses-gains conduction heat transfer (envelope) throughout the year in Sevilla.

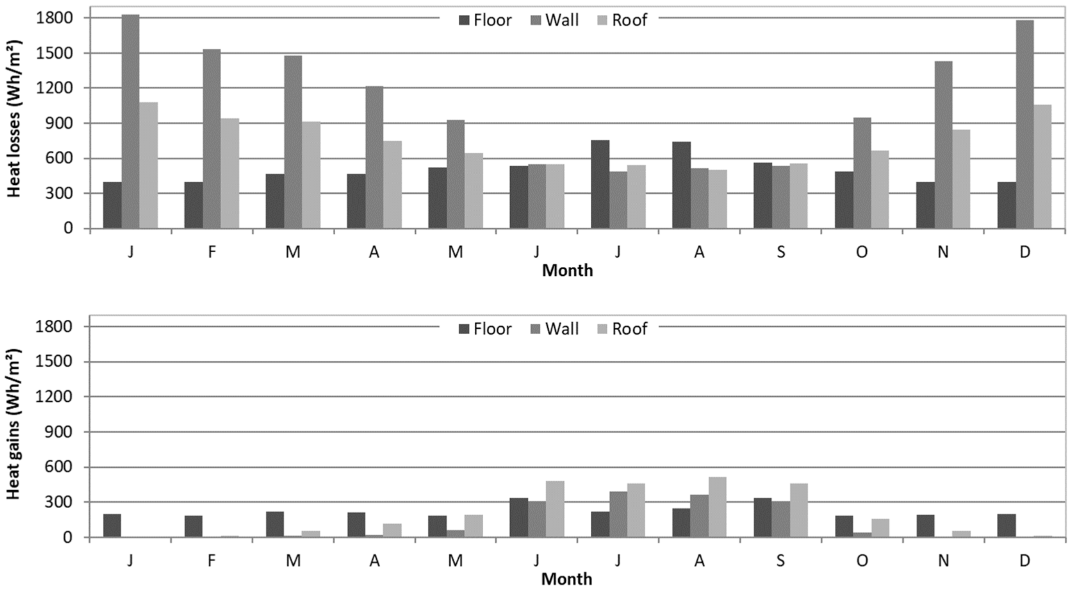

Figure 3. Energy losses-gains by conduction heat transfer (envelope) throughout the year in Soria.

The results show that heat losses increase on the roof and on the façade walls in cold periods, while the opposite happens on the basement. This fact is due to the thermal inertia of the ground, which allows dampening the thermal oscillations of the exterior maintaining a more constant temperature throughout the year. In addition, in the cold months, heat losses occur to a greater extent through the façade walls, exceeding 1200 Wh/m^2 in Seville (Figure 2) and 1800 Wh/m^2 in Soria (Figure 3), while in the hot months more stable values are reached in all the envelope construction elements (roof, floor, and façade walls) in Soria. In contrast, in summer, the ground in Seville (Figure 2) reaches levels above 1000 Wh/m^2, while the façade and roof maintain similar levels around 200–400 Wh/m^2. This behavior is largely explained by the solar irradiation received by the envelope, which depends on the inclination of the sun with respect to the façade walls and the roof.

Regarding heat gains, it is observed that they occur to a greater extent in the summer months, through the roof in Soria (Figure 3) and the façade walls in Seville (Figure 2), while through the ground they are practically non-existent in Seville, conserving around the same values in Soria. The heat gains are quite small in the building compared to the heat losses seen above.

3.2. Comparative Study of the Different Scenarios Studied

Simulations of the reference case show that the potential of the results is conditioned to 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. Therefore, it is important to note that buildings with low air renewal rates will have much greater energy saving potential with recycled materials.

Table 6 compares the total savings in heating, refrigeration and the sum of both in the two Spanish cities under study.

The results show that including recycled materials in various building construction elements is a success, as it gives a second life to the CDW generated and reduces not only the consumption of raw materials, but also the energy consumption of the building. Energy savings can range from 8% in Seville to 13% in Soria, being higher in heating than in cooling.

It is also observed that recycled materials used on the roof (Case 3) have a greater potential for energy savings than when they are located on the façade (Case 2), achieving up to 7% savings.

Table 6. Energy consumption of the building 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
SEVILLA							
Case 1	Renovations	64,328		26,291		90,619	
Case 2	Renovations	63,825	1%	26,709	−2%	90,534	0%
Case 3	Renovations	62,671	3%	26,338	0%	89,009	2%
Case 4	Renovations	61,999	4%	26,696	−2%	88,695	2%
Case 1	Envelope	17,076		6979		24,054	
Case 2	Envelope	16,936	1%	7087	−2%	24,023	0%
Case 3	Envelope	15,819	7%	6648	5%	22,467	7%
Case 4	Envelope	15,523	9%	6684	4%	22,207	8%
SORIA							
Case 1	Renovations	245,576		3189		248,765	
Case 2	Renovations	244,595	0%	3533	−11%	248,127	0%
Case 3	Renovations	242,994	1%	3460	−8%	245,606	1%
Case 4	Renovations	241,768	2%	3838	−20%	245,606	1%
Case 1	Envelope	52,772		685		53,457	
Case 2	Envelope	51,211	3%	740	−8%	51,951	3%
Case 3	Envelope	47,659	10%	679	1%	48,337	10%
Case 4	Envelope	45,572	14%	723	−6%	46,295	13%

Furthermore, the economic savings of reducing energy consumption in air conditioning can reach up to 14% for heating (Soria) or 4% for cooling (Seville). These results suggest that very isolated houses work better in cold climates such as Soria or in northern Spain. In hot climates, such as Seville or the south of Spain, isolated houses overwarm the indoor environment, and thus it works better in winter rather than in summer. However, the total consumption and economic cost is reduced, although to a lesser extent.

4. Conclusions

The research presented includes a representative part of currently existing recycled materials, as well as their most representative applications. Similarly, the thermal conductivity coefficient of several samples of cement and expanded clay with extruded polystyrene waste (XPS) has been experimentally determined (0.04 w/mK). These recycled materials can be an interesting alternative if they are used as thermal insulating materials in buildings, allowing thermal conductivity coefficients of up to 0.04 w/mK to be obtained.

Furthermore, this work shows the characteristics and energy balances in a representative building of the Spanish construction model in different climatic zones. The Spanish construction code promotes that energy gains/losses occur mainly due to air renewals (≈80%) of buildings, with the remaining ≈ 20% due to heat transfer through the envelope. Energy losses occur mainly through the glazing (36%) while in the roof and façade walls (21% and 30%, respectively) the impact is more moderate, dropping considerably in the ground (13%). These values show that some elements of the construction (walls, roof) of the building in which recycled materials can be implemented have a high potential for energy savings.

Regarding the energy evaluation of several construction solutions using recycled materials with CDW, as well as the comparison with traditional solutions, the following conclusions can be drawn:

- Energy savings can range from 8% in warm climates (e.g., Sevilla) to 13% in colder climates (e.g., Soria), being greater in heating than in cooling;
- Incorporating recycled materials into the roof presents greater energy savings potential (up to 7%) than when placed in the façade;

- Economic savings due to the reduction in the energy consumption of the cooling system can reach up to 14% for heating in colder climates (e.g., Soria) or 4% for cooling in warm climates (e.g., Seville).

The incorporation of recycled materials in various building construction elements has proven to be a success, as it reduces the consumption of raw materials and the energy consumption of the building. Future studies similar to the one carried out in this work are expected to contribute to the great environmental challenges needed to be faced today in order to achieve a cleaner and more sustainable planet.

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