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# Methodology for the environmental analysis of mortar doped with crumb rubber from end-of-life tires

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ABSTRACT

The construction sector is in a process of improvement towards sustainability. The study of the use of a waste as raw materials is an opportunity. This article aims to evaluate the environmental viability of incorporating recycled crumb rubber from end-of-life tires into a mortar. To this end, a life cycle assessment tool is implemented by applying the EPD methodology to assess the various categories of impact. A series of mortar alternatives were analyzed in which fine aggregate is replaced by a percentage of crumb rubber ranging from 10% to 40%: the proportion increases by 5% in each solution. The scope of the LCA is from cradle to gate as it is during the various stages that the greatest environmental impacts are incurred: including the extraction of raw materials, their transport, as well as the production process. The functional unit is that of producing 1 $m^3$ of mortar. The results obtained in this study show that the primary contributor to environmental impact is the cement production phase. On the other hand, the various alternatives evaluated achieved a 37.04% reduction in emissions of kg of $CO_2$, as well as a 41.83% reduction of abiotic depletion of fossil fuels when 40% of fine aggregate was replaced by crumb rubber. This study also demonstrates that the transport distance of recycled materials from their point of production to the mortar production plant is a decisive factor. Depending on that distance, the proposed solution can be rendered environmentally unviable. On a final note, it is important to underscore that the appropriate use of recycled aggregates in mortar is not only determined by strength but also environmentally. This research generates knowledge about the environmental benefits of using recycled materials in construction.

## 1. Introduction

The industrial construction sector is a key player in a countrýs economy and society. In Spain, for example, it constitutes 5.76% of the countrýs gross national product (GNP) [1]. This contribution is relies on some 1.3 million jobs found in this sector in Spain [2]. At the same time, the construction industry is well known to be a major consumer of raw materials and energy. Its activities contribute significantly to the problem of global warming, primarily by generating greenhouse gases (GHG).

Concrete is the most well-known and widely used material in the construction sector, second only to the industry's water consumption [3]. Its popularity is due to its remarkable mechanical properties, durability, and versatility [4], which make it an ideal material for construction. Concrete is a mixture composed of water, cement, sand, gravel, and admixtures. Of these components, cement is that which constitutes the greatest environmental burden, as it emits large amounts of $CO_2$ into the atmosphere during its production process. The European Cement Association estimates that in 2022 some 4.1 billion metric tons of cement were produced worldwide [5]. This means that for every ton of cement produced, between 0.62 and 0.97 metric tons of $CO_2$ are emitted [6]. Hence, this sector is responsible for around 8–9% of the worlds total $CO_2$ emissions [7].

Among all types of cements, the predominant material is clinker.

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*Abbreviations:* ELTs, End-of-life-tires; LCA, Life Cycle Assessment; CR, Crumb Rubber; GNP, Gross national product; GHG, Generating greenhouse gases; C&DW, Construction and demolition waste; NA, Natural aggregates; RAC, Recycled aggregates; GWP, Global warming potential; SIGNUS, Collective tire management system; SP, Superplasticiser SP; w/c, water/cement ratio; LCI, Life cycle inventory; EPDs, Environmental product declarations; ADFF, Abiotic depletion of fossil fuels.

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Clinker is the result of a limestone calcination process at very high temperatures (approximately 1400 °C ~ 1500 °C). In this calcination process, large amounts of $CO_2$ are emitted as calcium carbonate ($CaCO_3$) decomposes into CaO and $CO_2$. This reaction can represent 50% of the total $CO_2$ emissions generated by the cement production process [3]. The remaining $CO_2$ emissions come from the consumption of approximately 3000–4300 MJ of fuel energy and 120–160 kWh of electrical energy per ton of cement produced [8].

Consequently, a new field of research has coalesced around the objective of reducing the consumption of raw materials in the production of concrete and other construction materials such as mortar. For this reason, current research aims to cut down on the amount of cement as much as possible, by incorporating materials with pozzolanic properties, especially those derived from industrial processes, and, on the other hand, employing recycled materials instead of fine aggregates. Some such materials include fly ash, granulated blast furnace slag, silica fume, construction and demolition waste (C&D), glass, recycled tires, etc., [4]. To this end, several studies have revealed the technical feasibility of these types of concretes by demonstrating their mechanical and structural properties and possible applications [9–11].

Nevertheless, these studies focus on defining the mechanical and durability properties of doped concretes and mortars. The next step is to incorporate environmental implications into the results. For this purpose, Life Cycle Analysis (LCA) is the method utilized herein to quantify the environmental impacts of the products and services evaluated. This methodology taking into account a temporal scope and system boundary, allows the quantification of environmental impacts based on the previously analysed inputs and outputs of the system. Generally, the inputs to the system are energy flows, raw materials, water, etc., as well as outputs such as $CO_2$ emissions, liquid and solid waste. By applying this methodology, it is possible to obtain results such as those found by Teixeria et al. wherein they observe that the best environmental results occurred when 60% of cement was replaced by biomass fly ash [3]. Therefore, the amount Portland cement can be reduced, which is the foremost generator of $CO_2$ emissions during the production process. The aim is to create concretes with less environmental impact and that are more sustainable. Other research focuses on replacing natural aggregates (NA) with recycled aggregates (RAC). The results obtained in such studies confirm that, although there are no significant differences in some impact categories, such as global warming potential (GWP), in other impact categories, such as the depletion of mineral resources, there are some environmental advantages [12,13].

Of all the available recycled aggregates, crumb rubber (CR) derived from recycling end-of-life tires (ELTs) boasts remarkable potential. Bianco et al. outline the most common scenarios for ELTs. These include incineration, where ELTs provide heat and are generally used as a substitute for fossil fuels in clinker kilns for cement production [14]. On the other hand, recycling ELTs generates three by-products: metallic fibers, known as metallic scrap; textile fibers; and CR [15]. Both routes offer environmental advantages when compared to ELTs accumulating in landfills without any pre-treatment. Farina et al. show that the production of 1 metric ton of CR corresponds to a net life-cycle energy saving of 4236 MJ/mt, as well as a net greenhouse gas emission gain of 103 kg $CO_2$/mt. These results attest to the fact that CR has a remarkable environmental potential [16].

The most promising uses of CR are found in the field of civil engineering and construction elements: for example, generating asphalts for roads [16–18], as a drainage layer in flat roofs [19], incorporating it into structural elements such as vaults and bricks [20], given that CR can improve their thermal [21] and acoustic properties [22], as well as CR's use in concretes and mortars [18]. Specifically, in the field of CR-doped mortars is the research of Faizah et al. where they evaluated the dynamic properties of CR-doped mortar joints to produce a masonry wall. The results show that CR-doped mortar joints increase the damping coefficient by 11.45% when the wall is subjected to cyclic loading [23]. This can be a solution for the damping capacity of the walls and is a particular consideration in areas of high seismic activity. In the area of concrete applied to masonry is the research of Fakih et al. where they propose the development rubberized concrete interlocking brick. These bricks use different amounts of fly ash and CR in their composition, as a substitute for cement and fine aggregate. Among their most outstanding results, they show a decrease in thermal conductivity and therefore an increase in the thermal resistance of the wall of 62% rising from 0.106 $m^2 \cdot K/W$ to 0.171 $m^2 \cdot K/W$ [24]. Due to the improved thermal insulation properties of a wall made of such bricks, it would reduce the fuel needed to meet thermal needs and thus $CO_2$ emissions.

In Spain in 2021, 197,765 metric tons of ELTs were collected. Of this quantity, only 11.2% were reused, i.e. 22,469 metric tons. The remaining 75,296 metric tons of ELTs underwent various processes as indicated by the collective tire management system (SIGNUS) [25]. 104,794 metric tons, i.e. 58.93%, were used to produce rubber, steel, and textile granulation. Another 39.55%, – 70,324 metric tons - was utilized to produce cement by burning it as a substitute for traditional fuel. And the third procedure representing 1.48%, equivalent to 2,639 metric tons, was electrical energy production. Finally, 0.03%, or 60 metric tons, were used in Spain directly in civil projects without any kind of process, such as in walls or shock absorbers in ports. As a result of these data, it can be deduced that new uses for CR can be created, such as fine aggregate, which could thereby impact the 39.55% of ELTs which, as aforementioned, are burned to fuel cement production. Such a shift would mitigate the significant adverse effects on the environment involved in said process.

Therefore, this research focuses on environmental evaluating the addition of CR from ELT recycling as an aggregate substitute in mortar. For this purpose, several alternatives are examined in which different percentages of the NA is replaced by CR. The environmental analysis is performed by means of an LCA. Thus, and based on the results obtained, it is possible to contribute to achieving the United Nations Sustainable Development Goals [26]; and specifically, the thirteenth goal of climate action, given that using recycled materials reduces the carbon footprint of an activity.

## 2. Materials

The mortar modelled in this study consists of four main components: cement, natural aggregate, water, superplasticiser (SP), and CR. The following sections explain the principal characteristics of these materials.

### 2.1. Cement

The cement used to manufacture this mortar is CEM II/A-L 42.5R, as defined by European standards [27]. It has a characteristic strength of 42.5 MPa at 28 days and its clinker content ranges between 80 and 94% by weight. This type of cement is used to produce concretes with demanding mechanical requirements and it is also utilized for lightweight precast concrete, for exposed or architectural concrete parts, and to produce ready-mixed mortars.

### 2.2. Fine aggregate

The aggregate used is a fine aggregate of 0 to 4 mm in size and a density of 1634 $kg/m^3$. The aggregate comes from a quarry (VRESA, Navarra) where limestone is crushed to the specified dimensions.

### 2.3. Water

The water used is ordinary industrial water. Its characteristics are a pH of 7.9 and a sulphate content of 590 ppm.

### 2.4. Superplasticiser

The SP is RheoFIT 786 for semi-dry and precast concrete. It has a density of 1190 kg/$m^3$ and its main objective is to reduce the amount of water in a mortar mix, consequently achieving better hydration of cement and workability. The doses specified by the manufacturer range from 0.3 to 0.6% by weight of the cement.

### 2.5. Crumb rubber

As a replacement for fine aggregate, crumb rubber from a car and truck tire recycling operation at Indugarbi NFÚs S.L. plant is employed. This crumb rubber has a particle size of 1 – 4 mm and a density of 1150 kg/$m^3$.

### 2.6. Samples tested

The samples analyzed in this study were obtained from results developed previously by Sodupe et al. In this study the technical characteristics were evaluated, as well as the feasibility of producing precast elements with rubber doped mortar [20]. Table 1 displays the quantities of the components of each sample. As one can observe, the water/cement ratio (w/c) remains constant - equal to 0.8 - which implies that the quantities of water and cement remain the same throughout the study. The same applies to the amount of SP, with a value of 1.59. Thus, only the amount of fine aggregate varies and is replaced by an amount of CR. Therefore, different mortar samples are analysed. For instance, M_REF is the mortar sample without the addition of CR. M_10 indicates a mortar sample where 10% of the fine aggregate volume has been replaced by CR, and consecutively up to a percentage of 40%.

## 3. Methodology and case study

The life cycle analysis methodology is outlined by ISO 14040 [28] and ISO 14044 [29]. These standards specify the framework and terminology, as well as the phases involved in such a study. These are: i) definition of the objective and scope of the study; ii) life cycle inventory; iii) impact assessment; iv) interpretation of results. The scope and objectives express the purpose, objectives, and system boundary to be examined, as well as its respective functional unit. The life cycle inventory analyzes the necessary data of the product life cycle. In the penultimate stage of environmental assessment, the data presented in the life cycle inventory are classified, characterized, and normalized through a wide range of environmental assessment methodologies. These methodologies allow possible environmental impacts to be estimated according to scientific reasoning. The final stage is interpreting the results, wherein the information generated in the LCA can be identified and quantified. In this way, the results obtained can be communicated, and improvements to the system can be proposed [3]. These stages are not static and once defined they do no remain immobile, on the contrary, there is constant interaction among them throughout this dynamic process.

### 3.1. Goal and scope

The main objective of this study is to conduct an environmental comparison of different mortar alternatives. For each mortar alternative, the amount of aggregate is modified and replaced by a percentage of CR. In this way, the environmental impacts of each sample can be evaluated according to its CR and aggregate content. Therefore, based on a comparative analysis of the characteristic strength results presented in Table 1, more general conclusions can be drawn to inform solutions that integrate the concept of sustainable construction.

### 3.2. Functional Unit

The functional unit is the reference unit for which the environmental impacts are calculated [30]. In the case of previous research in this field [31–34], the functional unit has been defined as 1 $m^3$ of concrete, given that this unit is representative and comprehensible in the construction and civil engineering sectors. In the case of this study, the functional unit is also defined as 1 $m^3$ of mortar.

### 3.3. System boundary

Mortar is a widely used material in construction, particularly in the construction of buildings. UNE-EN ISO 14040 and UNE-EN ISO 14044 state that buildings have their own unique stages within the LCA of a construction. Their respective stages and phases are listed in Table 2.

In the case of mortar production, the production phase, which encompasses the extraction of raw materials and production processes, has the greatest environmental impact on the LCA [6]. In addition, it is assumed that the evaluated mortars' behavior will remain adequate throughout their lifetime; The phases of construction, use, maintenance, demolition and recycling have an impact on the environment. In this research, these last phases are currently identical for conventional mortar and a doped mortar. For this reason, it was decided not to include

**Table 2**
Phases and processes of the construction life cycle.

| Phase | Process |
|---|---|
| Production | A1: Extraction of raw materials |
| | A2: Transport to factory |
| | A3: Manufacturing |
| Construction | A4: Product transport |
| | A5: Product installation and construction process |
| Product use | B1: Use |
| | B2: Maintenance |
| | B3: Repair |
| | B4: Replacement |
| | B5: Refurbishment |
| | B6: Operational energy use |
| | B7: Operational water use |
| End of Life | C1: Deconstruction and demolition |
| | C2: Transport |
| | C3: Waste management |
| | C4: Final disposal |

**Table 1**
Dosage characteristics of tested mortars (M_REF = 0% CR; M_10 = 10% CR; M_15 = 15% CR; M_20 = 20% CR; M_25 = 25% CR; M_30 = 30% CR; M_35 = 35% CR; M_40 = 40% CR).

| Notation | w/c | SP (l) | Water (kg) | Cement (kg) | Fine aggregate (kg) | CR (%) | CR (kg) | Density (kg/$m^3$) | Strength 7 days (MPa) | Strength 28 days (MPa) |
|---|---|---|---|---|---|---|---|---|---|---|
| M_REF | 0.80 | 1.59 | 250.85 | 312.62 | 1535.20 | 0 | 0.00 | 2100.25 | 18.90 | 24.20 |
| M_10 | 0.80 | 1.59 | 250.85 | 312.62 | 1304.50 | 10 | 144.90 | 2014.55 | 17.58 | 20.04 |
| M_15 | 0.80 | 1.59 | 250.85 | 312.62 | 1239.90 | 15 | 218.80 | 2023.75 | 15.27 | 17.96 |
| M_20 | 0.80 | 1.59 | 250.85 | 312.62 | 1024.90 | 20 | 256.20 | 1846.13 | 8.68 | 15.88 |
| M_25 | 0.80 | 1.59 | 250.85 | 312.62 | 958.50 | 25 | 319.50 | 1843.00 | 9.75 | 13.80 |
| M_30 | 0.80 | 1.59 | 250.85 | 312.62 | 934.70 | 30 | 400.60 | 1900.28 | 11.63 | 11.72 |
| M_35 | 0.80 | 1.59 | 250.85 | 312.62 | 835.70 | 35 | 450.00 | 1850.83 | 9.48 | 9.64 |
| M_40 | 0.80 | 1.59 | 250.85 | 312.62 | 731.20 | 40 | 487.50 | 1783.80 | 7.35 | 7.56 |

them. We have focused on the production phase; it will be interesting to develop future research on the rest of the phases in order to detect possible differences or improvements. Thus, the system boundary of this study consists of a cradle-to-gate LCA.

Fig. 1 shows the system boundary under study and that which falls beyond the limits. The analyzed system comprises the extraction of raw materials from their natural state in the environment to the implementation of their respective production processes to obtain the raw materials necessary to produce mortar (fine aggregate, cement, water). For each process, the necessary resources, i.e., fuels, machinery, energy, materials, transport, etc., are also defined.

In this study, the process of obtaining crumb rubber from ELT recycling was modelled as shown in Fig. 2. To this end, the current literature defines the process as a sequence of stages [14,15,35]. The first step is collecting ELTs from the recycling plant. The next step is grinding the ELTs to a size within the range of 7–10 cm. The equipment required in this phase is a double shaft grinder with a single blade. The next process is a second grinding to reduce the elements to a size of approximately 2 cm. For this purpose, the equipment consists of two concentric cylinders: the external cylinder is fixed and equipped with steel blades, while the internal cylinder is rotating and is also equipped with blades on the outside which are fitted to the outer cylinder. The product from the second grinding process is then transported on conveyor belts to the third stage. During this transition, the rest of the elements that make up the tire - textile fibres and metallic fibres - are separated using magnetic separators. The last stage is granulating the material to dimensions of less than 1 mm. The machine tasked with this process is similar to the previous process: consisting of two discs, one fixed and one rotating, both of which have blades. A pneumatic system equipped with fans and a cyclone is used to produce the forward movement of the material. Thus, optimum granulation is achieved and ungrained material is avoided. Finally, the crumb rubber is packaged in plastic big bags and prepared for marketing and transport. The inputs and flows involved in this production process are electrical energy, diesel fuel, water, industrial lubricant, the metal blades from the respective production process, as well as plastic big bags.

### 3.4. Life cycle inventory (LCI)

The next step is to create the life cycle inventory. This is a very important stage as the inputs and outputs of the new system under study as well as the respective quantities must be identified. A deficiency in the characterization of the flows of energy, matter, processes etc., can lead to erroneous results and thus to their subsequent misinterpretation. The following sections explain how the data used in the LCI were obtained, as well as justifications for the various assumptions made in certain cases.

#### 3.4.1. Data source

The LCA modelling was conducted with the SimaPro 9.4 software. For the development of the LCI, primary data were used to define the transport distances of the CR. The rest of the data used came from secondary data sources. Among all the available databases, the Ecoinvent v.3 database [36], as well as the ELCD database (European Life Cycle Databases), were used primarily. In addition, due to the lack of information and data on certain processes, such as the production of CR from an ELTs recycling process, current research and bibliographies were also referenced [14,16,17].

#### 3.4.2. Raw materials (A1)

This stage comprises the processes of extracting and obtaining the raw materials present in the mortar product. The following raw materials have been modelled for this LCA: cement, fine aggregate, and water. SP was not considered within the LCI [37]. Although the environmental impacts of this product during its production phase are high. Given its dosages (less than 1% by mass), it does not contribute significantly to the environmental impact of the functional unit [38]. Table 3 shows the various quantities of each of the raw materials used.

*3.4.2.1. Crumb rubber.* There is no information available in the Ecoinvent database on the CR production system, this gap is also found in previous research [16,17] where the is a clear lack of information about this process in this type of database. Therefore, research [19,39] performing an LCA involving CR obtains data from tire recycling plants where CR is produced. To recreate the CR production process and its respective life cycle inventory, the authors Bianco et al. modelled the tire recycling process for CR production [14], according to the system boundary shown in Fig. 2. In this LCI, parameters were adjusted to fit data from Spain.

In order to improve the proposed configuration of the CR production process, and as established by Bressi et al., two sub-processes must be carried out within the main CR process [17]. Firstly, the so-called *plastic big bags* used at the end of the CR production process for subsequent storage and distribution to consumption points must be produced.

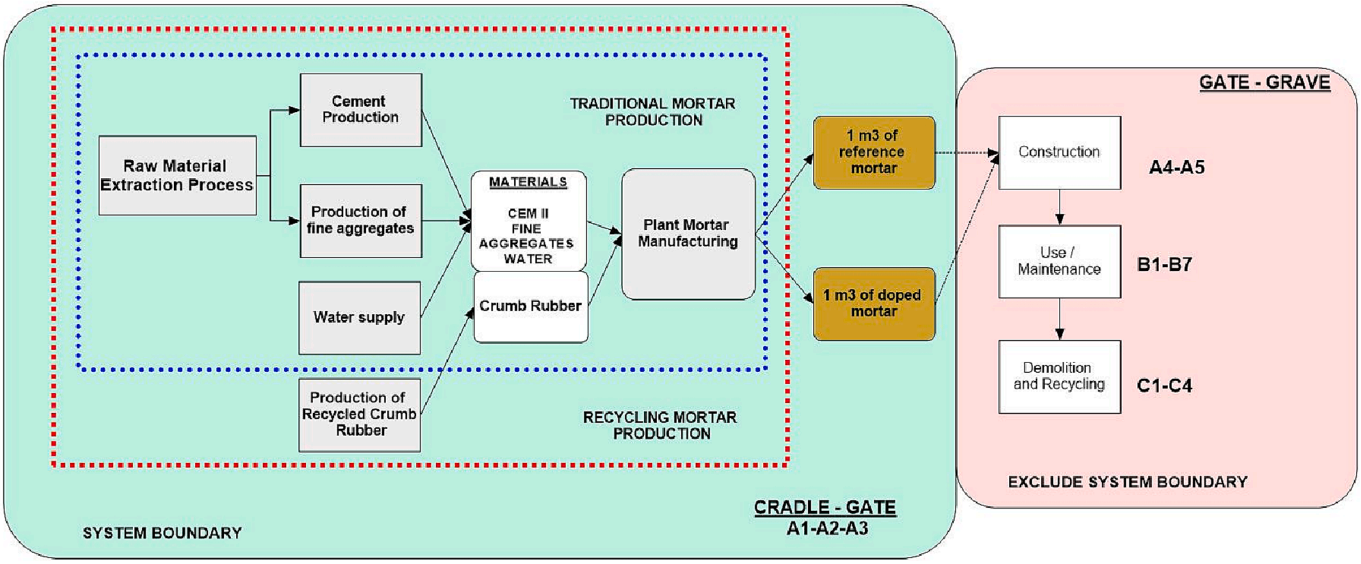

**Fig. 1.** System boundary for mortar production system. The processes are shown in grey boxes, the materials in white boxes, and the functional unit in brown.

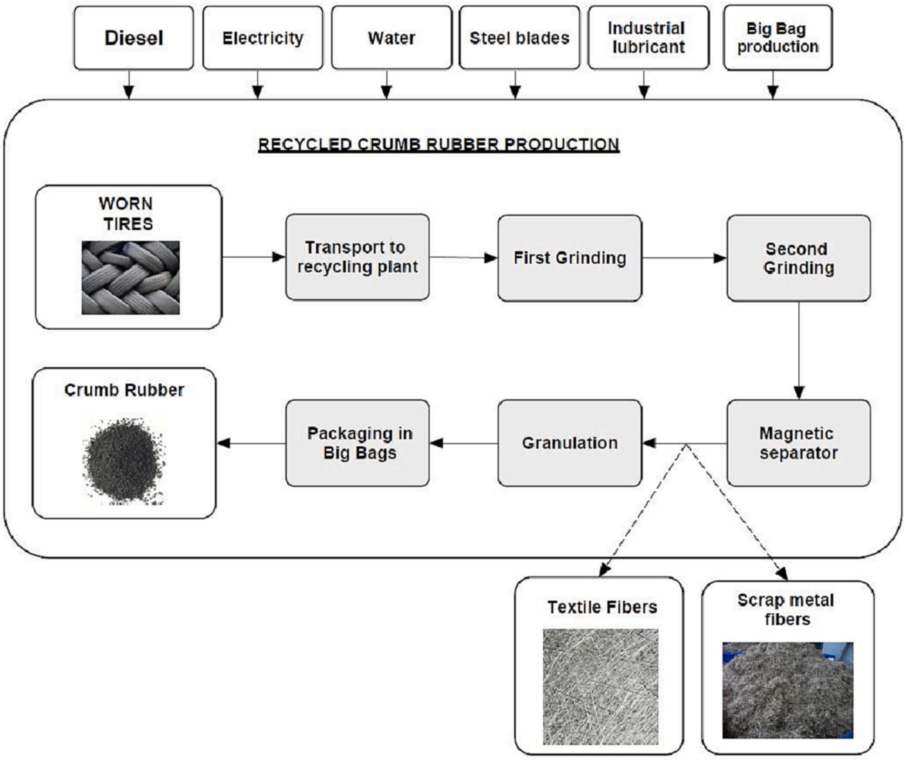

**Fig. 2.** System boundary for crumb rubber production.

**Table 3**
Inventory of raw materials.

| Inventory | Unit | Amount | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | | M_REF | M_10 | M_15 | M_20 | M_25 | M_30 | M_35 | M_40 |
| Cement | kg | 312.62 | 312.62 | 312.62 | 312.62 | 312.62 | 312.62 | 312.62 | 312.62 |
| Tap Water | kg | 250.85 | 250.85 | 250.85 | 250.85 | 250.85 | 250.85 | 250.85 | 250.85 |
| Fine aggregate | kg | 1535.20 | 1304.50 | 1239.90 | 1024.90 | 958.50 | 934.70 | 835.70 | 731.20 |
| CR | Kg | – | 144.90 | 218.80 | 256.20 | 319.50 | 400.60 | 450.00 | 487.50 |

**Table 4**
Inventory for production of 1 kg of plastic big bags [17].

| Input item | Unit | Amount |
|---|---|---|
| Diesel | Kg | 6.81E-05 |
| Polyethylene foam | Kg | 1.00 |
| Polyethylene low density granulate | Kg | 0.10 |
| Polypropylene granulate | Kg | 0.90 |
| Output item | Unit | Amount |
| Plastic big bag | Kg | 1 |
| Emissions to air and water | Unit | Amount |
| Butyl acetate [ecoinvent long-term to air] | kg | 0.0097 |
| Carbon dioxide [inorganic emissions to air] | kg | 0.00041 |
| Carbon monoxide [Inorganic emissions to air] | kg | 8.06E-06 |
| Ethanol [Organic emissions to fresh water] | kg | 0.00194 |
| Methane [Organic emissions to fresh water] | kg | 3.26E-08 |
| Nitrogen dioxide [Inorganic emissions to air] | kg | 4.10E-06 |
| Sulphur oxides [Inorganic emissions to air] | kg | 5.00E-7 |
| Toluene [ecoinvent long-term to air] | kg | 0.00399 |

**Table 5**
Inventory for production of steel blades [16,17].

| Input item | Unit | Amount |
|---|---|---|
| Steel unalloyed production | kg | 0.29 |
| Hot rolling steel processing | kg | 0.29 |
| Sheet rolling steel processing | kg | 0.29 |
| Electricity | MJ | 0.00103 |
| Output item | Unit | Amount |
| Steel Blade | kg | 0.29 |

Table 4 shows the inventory for creating 1 kg of plastic big bags.

Secondly, the production process of low alloy steel blades must also be modelled, given that the tire recycling process consumes a significant amount of this product. To manufacture the steel blade, three sub-processes are involved. According to Bressi et al. the first one is steel production; this material then undergoes hot rolling and concludes with sheet rolling [17]. Table 5 lists the inventory used to manufacture steel cutting blades.

Once these sub-processes are defined, the inventory for the tire recycling process and CR production can be defined. Table 6 details the inventory. It should be noted that the tire recycling production process for CR production entails a production yield of 1000 kg of CR, 290 kg of metal fibers, and 160 kg of textile fibers, for every 1450 kg of ELTs. However, these co-products, such as a metal fibers and textile fibers can be recycled and used in other processes. Farina et al. state that due to the high market value of scrap metal fibers, 90% of them can be recycled [16]. Therefore, a total of 261 kg of scrap metal fibers can be recycled, generating a waste of 29 kg of scrap metal fibers. In the case of the textile fibers modelled in this study, they are subjected to an incineration process to obtain thermal energy with a percentage of 100% utilization.

**Table 6**
Inventory for CR production from tire recycling process.

| Input item | Unit | Amount |
|---|---|---|
| Tires for recycling | kg | 1450 |
| Steel blade | kg | 0.29 |
| Plastic big bag | kg | 1.85 |
| Tap Water | kg | 220 |
| Lubricating oil | kg | 0.04 |
| Diesel | MJ | 111 |
| Electricity medium voltage | kWh | 384 |
| Output item | Unit | Amount |
| CR | kg | 1000 |
| Scrap metal fibers | kg | 261 |
| Scrap waste | kg | 29 |
| Textile fibers | kg | 160 |

### *3.4.3. Transport (A2)*

This section explains the transport scenarios adopted for each of the raw materials used in mortar production. This covers from the raw material production plant to the mortar production plant. Transport is a highly important factor as the environmental load associated with it is significant [38]. The units defined for the transport process is metric tons per kilometer (mt·km). The transport modelling, for the different materials, is through the use of a lorry. This lorry has a total weight of 23.5 metric tons and a load capacity of 23 metric tons. The fuel used is diesel. In terms of emissions regulations, and in line with previous research [40], transport is modelled under EURO 6 [41]. This restricts emissions of particulate matter (PM), nitrogen oxides ($NO_x$) and carbon dioxide ($CO_2$) more restrictively. In SimaPro this process has the following designation “Transport, freight, lorry > 32 metric ton, EURO 6 {RER} transport, freight, lorry > 32 metric ton, EURO 6 | Cut-off, U”.

*3.4.3.1. Fine aggregates.* The fine aggregates come from a local quarry. The *National Association of Aggregate Manufacturer Entrepreneurs* provides a map of Spain indicating the companies producing fine and coarse aggregates [42]. This information reveals that the distance from quarries to concrete and mortar production plants usually ranges from 15 to 20 km. In the present study, a distance of 20 km was considered. This decision is supported by Clement et al. as aggregates are usually sourced from within a short range of distance due to their relative abundance [43]. Table 7 shows the various values applied to the alternatives studied.

*3.4.3.2. Cement.* Regarding cement production in Spain, there are a total of 35 industries directly associated with this economic activity. The majority are located close to large urban and coastal municipalities, which allows for distribution to secondary areas. This is why cement transport distances range from 50 to 400 km [43], with an average of 200 km. This average value of cement transport to the mortar production plant is considered herein. In the alternatives analyzed in this study, the amount of cement does not vary. Consequently, the transport variable is 4,762.52 mt·km.

*3.4.3.3. Crumb rubber.* Two distinct transport distances must be specified for this raw material. The first distance involves transporting ELTs from their collection point to the recycling plant. A transport study was conducted by the SIGNUS organisation [44]. It provides information on the locations of ELT collection and recycling plants. In the case of the present study, the tire recycling plant is located in the municipality of Murillo el Fruto (Navarra). Its main ELT supplier is located in the municipality of Ballariáin (Navarra). Therefore, the distance between the main ELT collection point and the tire recycling plant is 80 km. This distance is similar to that assessed by Farina et al. where they establish an average distance of 75 km [16]. The impacts associated with this first phase of ELT transport are included in the CR production process. Once the CR is produced in the tire recycling plant, it must be transported to the mortar production plant, which in this study is located in Logroño (La Rioja). This distance is 100 km. Table 8 displays the various transport values used for each of the alternatives evaluated.

**Table 7**
Fine aggregates transport distance as a function of the alternative evaluated.

| Sample | Fine aggregates (mt) | Distance (km) | Transport (mt·km) |
|---|---|---|---|
| M_REF | 25.04 | 20 | 500.70 |
| M_10 | 24.80 | 20 | 496.09 |
| M_15 | 24.74 | 20 | 494.80 |
| M_20 | 24.52 | 20 | 490.50 |
| M_25 | 24.46 | 20 | 498.17 |
| M_30 | 24.43 | 20 | 488.69 |
| M_35 | 24.34 | 20 | 486.71 |
| M_40 | 24.23 | 20 | 484.62 |

### *3.4.4. Production process (A3)*

After the raw materials arrive at the production plant, the inputs necessary to produce the mortar mix must be addressed. For this purpose, the energy consumption of the machines involved in this process, i.e., mixers, conveyor belts, dosing machines, etc., must be taken into consideration. The energy used in concrete and mortar production plants is electrical. Clement et al. define power and energy consumption [43]. These variables depend on a plant’s production capacity. In the case of this study, the productive capacity of the plant is considered to be high. Table 9 shows the power, electrical energy consumption as primary energy, and emissions emitted, all according to the plańts production capacity.

Given the functional unit of 1 $m^3$ of mortar, the energy consumption of mixing the raw materials is defined as 1.61 $kWh/m^3$. In the SimaPro software, this energy consumption is modelled through an electrical energy process for the electricity grid in Spain.

### *3.5. Life cycle impact assessment*

In this stage of the LCA, the potential effects on the environment and humans are assessed. These effects stem from all the elements identified in the LCI. The impact assessment involves a number of mandatory intermediate steps. The first of these is to select the impact categories. The second step is classification, that is, the LCI results are assigned to impact categories. And lastly, characterization, wherein impact indicators for each category are calculated based on the characterization factors. These three phases are mandatory when conducting an LCA. However, there are some optional subsequent steps: normalization, grouping weighting, data quality analysis.

Nowadays, a wide range of methodologies are available to assess environmental impacts. The choice of methodology, however, is critical. This is because the chosen methodology must include those impact categories wherein the product in question can have significant influence. In the case of commercial construction materials such as the production of mortars, concrete, and building materials, their LCAs are generally described by environmental product declarations (EPDs). These EPDs provide information through a reliable, transparent, comparable, and verifiable environmental profile of the product. Therefore, in this study the EPD 2018 methodology (available in the SimaPro

**Table 8**
CR transport distances depending on the alternative evaluated.

| Sample | CR (mt) | Distance (km) | Transport (mt·km) |
|---|---|---|---|
| M_10 | 23.64 | 100 | 2364 |
| M_15 | 23.72 | 100 | 2372 |
| M_20 | 23.76 | 100 | 2376 |
| M_25 | 23.82 | 100 | 2382 |
| M_30 | 23.90 | 100 | 2390 |
| M_35 | 23.95 | 100 | 2395 |
| M_40 | 23.99 | 100 | 2399 |

**Table 9**

Consumption in mortar production plant [4339].

| Plant productivity | Production capacity ($m^3/h$) | Specific Power ($kW/m^3$) | Specific consumption ($kWh/m^3$) | Primary Energy ($MJ/m^3$) | Emissions of $CO_2$ ($kg\ CO_2/m^3$) |
|---|---|---|---|---|---|
| Low | 40 | 2.08 | 1.41 | 8.76 | 0.425 |
| Medium | 100 | 1.83 | 1.51 | 9.38 | 0.455 |
| High | 180 | 2.01 | 1.61 | 9.95 | 0.483 |

software) was applied. This methodology uses a total of eight impact categories as shown in Table 10. Most of the impact categories are taken directly from the CML-IA methodology (eutrophication, global warming potential, ozone layer depletion, and abiotic resource depletion), and some from the non-reference methodology CML-IA (acidification). From the AWARE methodology, the water scarcity impact category was selected, and photochemical oxidations from the ReCiPe 2008 methodology.

## 4. Results: Interpretation and discussion

Finally, the last stage of the LCA in this study is to interpret and discuss the results. In general, an LCA on concretes and mortars is differentiated by its more significant effect on some impact indicators: the global warming indicator (GWP) and the abiotic depletion of fossil fuels (ADFF). The latter is of notable importance as it is known worldwide and is the most representative indicator of global warming [31]. On the other hand, fossil fuel depletion indicates the depletion of non-living natural resources (minerals and fossil fuels). These indicators are selected as the most representative since the production of concrete and mortar entails significant consumptions of raw materials, fuels, etc., and consequently an increase in greenhouse gas emissions.

### *4.1. Reference mortar*

Fig. 3 depicts the impacts produced by each of the raw materials included in 1 $m^3$ of reference mortar, as well as their production process. In all the impact indicators assessed, except the category of water scarcity, the cement production process is that which generates the most impact, at over 80%. This is followed by the impacts generated by the raw material fine aggregate. The third most impactful process is mortar production, i.e., energy consumption and emissions in the mixing plant itself. Finally, the raw material water has hardly any impact on the categories assessed, with values of less than 0.5%, except for the water scarcity impact category. In this category, fine aggregate has the highest impact with 84%, due to its high-water consumption in the mining and extraction processes. In addition, the raw material water itself reaches a value of 4.6% due to its use in the mixing of 1 $m^3$ of mortar. And finally, there is a value of −0.9% in the mortar production process. This is because surplus water in the production plant is treated, thus rendering it usable for subsequent uses.

Finally, it should be noted that fine aggregate also affects the categories of photochemical oxidation, ozone layer depletion, acidification, and eutrophication. According to Suárez et al., aggregate production is usually conducted by blasting with explosives, which produces substances such as ammonia and $NO_X$ that affect acidification [45], in addition to various volatile organic compounds and particulate emissions that affect photochemical oxidation.

**Table 10**

Impact indicators in the EPD methodology.

| Impact Categories | Unit |
|---|---|
| Acidification | kg $SO_2$ eq |
| Eutrophication | kg $PO_4$ eq |
| Global warming (GWP100a) | kg $CO_2$ eq |
| Photochemical oxidation | kg NMVOC |
| Abiotic depletion, elements | kg Sb eq |
| Abiotic depletion, fossil fuels (ADFF) | MJ |
| Water scarcity | $m^3$ eq |
| Ozone layer depletion | kg CFC-11 eq |

Of all the impact indicators assessed, ADFF and GWP stand out. In the ADFF category, the cement production process consumes the most energy, constituting 86.11% of the total. This is followed by the raw material process at 11.34%, and finally 2.49% for the mixing process. The raw material water consumes 0.06%. In line with the consumption of fossil fuels are the $CO_2$ emissions, which are reflected in the GWP category. The various stages are ordered in the table below according to the amount of emissions they emit. The raw material cement production accounts for 94.07%. The rest is divided into 3.54% for the fine aggregate production process. 2.27% for mortar production and mixing process, and the raw material water represents 0.02%. Table 11 shows the $CO_2$ emissions according to each defined process, as well as the MJ used in each stage. The result of 270 kg $CO_2/m^3$ falls within the range established by Kurda et al. of 170 – 400 kg $CO_2/m^3$. This study evaluated various concrete mixes incorporating different amounts of aggregates and binders [13].

### *4.2. Overall assessment of proposed alternatives*

For this general evaluation of the results, three interpretation scenarios have been defined. Scenario 1 (E1) evaluates exclusively the CR from the ELTs recycling process as a co-product used to produce doped mortars. In other words, this scenario only deals with the production process of ELT recycling with its respective consumption of energy, fuel, transport, etc. In scenario 2 (E2), each co-product produced is assigned a weight factor ($w_i$) in order to incorporate the respective flows of energy and material used in the ELT recycling process. These weight factors are a function of the by-product yield obtained from the ELT recycling process: for CR, a weight factor of 0.6897 is assigned; for scrap metal fibers, 0.20; and finally for textile fibers, 0.1103. With this scenario, the impacts produced can be evaluated according to each material obtained in the process. However, these two scenarios above do not address all the co-products obtained from the ELT recycling process. ELTs can be used in other production processes wherein there can generate an environmental improvement. For example, the co-product scrap metal fibers can be recycled to produce low alloy steel. Thus, a portion of the virgin materials that comprise low-alloy steel are not extracted. In addition, textile fibers are most frequently incinerated to obtain thermal energy. Consequently, scenario 3 (E3) provides a more comprehensive picture of the benefits that the ELT recycling process can offer.

#### *4.2.1. Results scenario 1*

Table 12 shows the results obtained for E1. It includes the various alternatives evaluated in terms of their CR content. In addition to their results in terms of the impact indicators evaluated with the EPD methodology, Fig. 4 provides a graphical representation.

As can be observed in the results, as the amount of CR aggregate increases, the environmental impact grows as well. This is because the ELT recycling production process involves a series of material and energy flows, as well as transport processes, which cause the sum of these activities to produce greater environmental loads than the production of natural fine aggregate. The increased environmental load is mainly due to the ELT transport process. For this case study, the tires are transported 80 km from the collection area to the ELT recycling plant, and then the CR obtained is transported another 100 km to the mortar production plant. Thus, fuel expenditure in transport is reflected in the category of

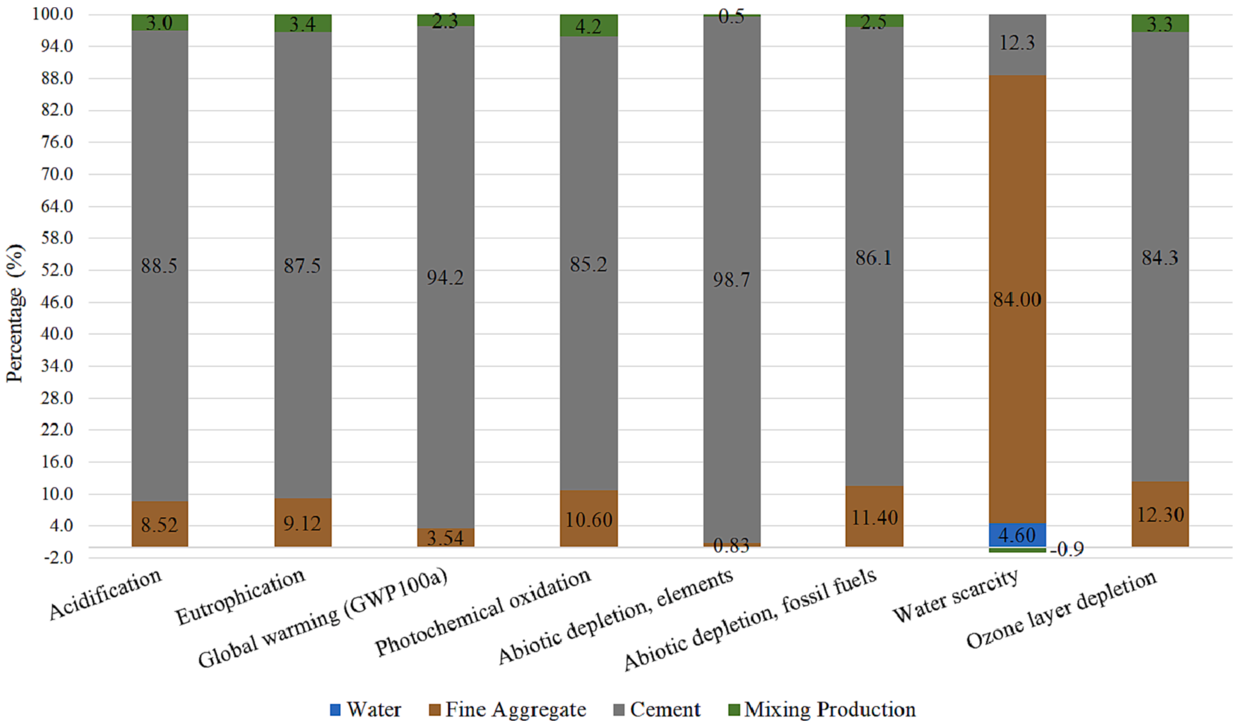

**Fig. 3.** LCA results for production of 1 m$^3$ of reference mortar according to indicator.

**Table 11**
GWP and ADFF indicators for production of 1 m$^3$ of reference mortar.

| Stage | GWP (kg $CO_2$ eq) | ADFF (MJ) |
|---|---|---|
| Production of 1 m$^3$ | 270 | 1084.65 |
| Raw material cement | 254 | 0.65 |
| Raw material fine aggregate | 9.56 | 123 |
| Raw material water | 0.056 | 934 |
| Mixing Production | 6.14 | 27 |

abiotic depletion of fossil fuels; in the case of the M_40 sample it increased by 49% in comparison to the M_REF alternative. As a result, due to the fuel combustion involved in transport, the emission of nitrogen oxides ($NO_x$), carbon oxides ($CO_x$), volatile organic compounds, and particulate emissions deplete the ozone layer [45]. This impact is reflected in the ozone layer depletion category which increases by 54%. In the global warming category, there is a 22% increase compared to the M_REF alternative. The influence of transport can also be observed in the categories of acidification and eutrophication with increases of 46% and 37% respectively between M_40 and M_REF.

However, in the category of water scarcity, if alternative M_20 and M_REF are compared, there is a reduction of 3%, as a total of 230.6 kg of natural fine aggregate is avoided and water consumption is key in producing this material. In general, the results concord with previous research. For example, Marinkovic et al. state that the production of RAC is slightly environmentally superior to the production of NA because of the transport process [12], a finding supported by the current study. However, this difference may represent a new advantage for RAC, as nowadays sources of NA are becoming increasingly scarce near urban areas, and therefore near production centers as well.

### 4.2.2. *Results scenario 2*

Table 13 shows the results obtained from E2, and Fig. 5 is their graphical representation.

If E1 is taken as the point of reference, the results demonstrate that there has been a reduction in all the impact categories. This is primarily because in E2 the respective environmental load is attributed to the CR through the weight factors. This is in contrast with E1, where all material flows and processes leading to a series of impacts were directly attributed to the RAC. As an example of the most notable results, the GWP between the alternatives M_REF and M_40 is increased by 16.92% and previously in E1 it increased by 22%. Other categories such as abiotic depletion of fossil fuels and ozone layer depletion increased by 41.40% and 47% respectively between the M_REF and M_40 alternatives. Compared to E1, this is a reduction of 7.6% and 7% respectively. However, as in E1, the use of CR from an ELT recycling process leads to greater impacts in several categories as the amount of CR in the mortar increases, due to the transport of CR.

**Table 12**
LCA results according to EPD method – E1.

| Indicator | Unit | MREF | M10 | M15 | M20 | M25 | M30 | M35 | M40 |
|---|---|---|---|---|---|---|---|---|---|
| Acidification | kg $SO_2$ eq | 0.607 | 0.760 | 0.84 | 0.874 | 0.942 | 1.030 | 1.080 | 1.120 |
| Eutrophication | kg $PO_4$ eq | 8.38E-02 | 9.85E-02 | 1.06E-01 | 1.09E-01 | 1.16E-01 | 1.25E-01 | 1.30E-01 | 1.33E-01 |
| Global warming (GWP100a) | kg $CO_2$ eq | 270 | 292 | 304 | 309 | 319 | 332 | 339 | 345 |
| Photochemical oxidation | kg NMVOC | 0.557 | 0.660 | 0.714 | 0.735 | 0.781 | 0.842 | 0.877 | 0.902 |
| Abiotic depletion, elements | kg Sb eq | 9.27E-04 | 1.01E-03 | 1.05E-03 | 1.07E-03 | 1.11E-03 | 1.16E-03 | 1.19E-03 | 1.21E-03 |
| Abiotic depletion, fossil fuels | MJ | 1084.65 | 1400 | 1570 | 1640 | 1780 | 1960 | 2070 | 2150 |
| Water scarcity | m$^3$ eq | 112 | 112 | 115 | 105 | 107 | 113 | 111 | 108 |
| Ozone layer depletion | kg CFC-11 eq | 1.03E-05 | 1.40E-05 | 1.59E-05 | 1.67E-05 | 1.83E-05 | 2.05E-05 | 2.17E-05 | 2.26E-05 |

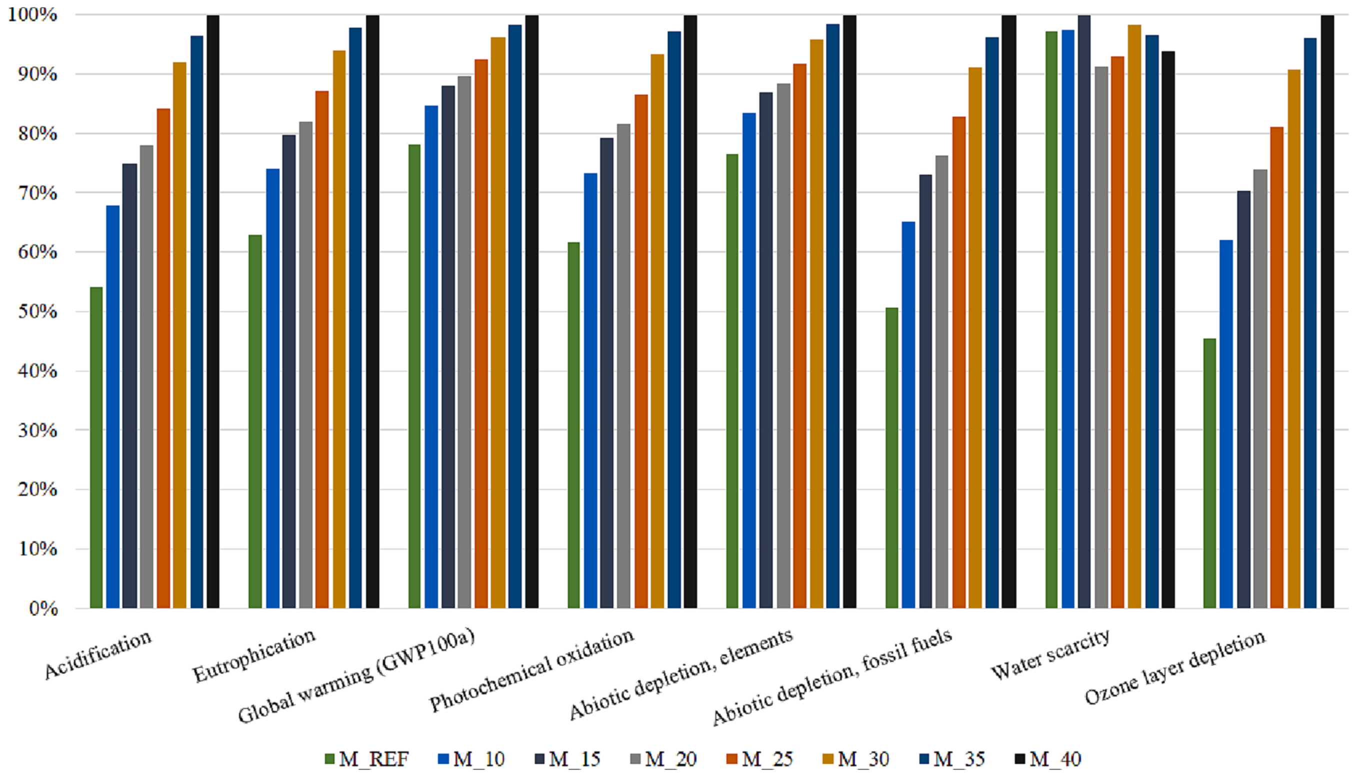

**Fig. 4.** LCA results for mortar alternatives according to EPD methodology – E1.

**Table 13**
LCA results according to EPD method – E2.

| Indicator | Unit | MREF | M10 | M15 | M20 | M25 | M30 | M35 | M40 |
|---|---|---|---|---|---|---|---|---|---|
| Acidification | kg $SO_2$ eq | 0.607 | 0.715 | 0.773 | 0.795 | 0.844 | 0.909 | 0.945 | 0.972 |
| Eutrophication | kg $PO_4$ eq | 8.38E-02 | 9.45E-02 | 1.00E-01 | 1.02E-01 | 1.07E-01 | 1.14E-01 | 1.17E-01 | 1.20E-01 |
| Global warming (GWP100a) | kg $CO_2$ eq | 270 | 286 | 295 | 298 | 305 | 315 | 321 | 325 |
| Photochemical oxidation | kg NMVOC | 0.557 | 0.631 | 0.672 | 0.685 | 0.718 | 0.765 | 0.789 | 0.807 |
| Abiotic depletion, elements | kg Sb eq | 9.27E-04 | 9.84E-04 | 1.01E-03 | 1.05E-03 | 1.05E-03 | 1.09E-03 | 1.10E-03 | 1.12E-03 |
| Abiotic depletion, fossil fuels | MJ | 1090 | 1320 | 1440 | 1490 | 1590 | 1730 | 1800 | 1860 |
| Water scarcity | $m^3$ eq | 112 | 107 | 108 | 97.4 | 97.4 | 101 | 98.2 | 94.2 |
| Ozone layer depletion | kg CFC-11 eq | 1.03E-05 | 1.30E-05 | 1.44E-05 | 1.50E-05 | 1.62E-05 | 1.78E-05 | 1.88E-05 | 1.94E-05 |

#### 4.2.3. Results scenario 3

The case of E3 hypothesizes that the co-products of scrap metal fibers are sent to a recycling and melting process in an electric arc furnace to produce low alloy steel. On the other hand, textile fibers are envisaged to be used to produce thermal energy for industrial processes. An incineration treatment for thermal energy production is modelled. Table 14 displays the results obtained for the various impact categories, depending on the alternative evaluated. Fig. 6 shows their graphical representation.

Interpreting the results reveals that in E3, the addition of CR to the mortar diminishes environmental impacts. For instance, in the GWP impact category, there is a 37.04% reduction in $CO_2$ kg between the alternatives M_REF and M_40. This difference is derived from a decrease in fossil fuel consumption as reflected in the category abiotic depletion of fossil fuels where the reduction results in a 41.83% difference between the extreme alternatives. This drop comes from recycling scrap metal fibers. Since the recycling of scrap metal fibers avoids extracting natural minerals that comprise steel. This observation is supported by Suarez et al. which examines the recycling of aggregates from construction and demolition waste [45]. In this case, steel is obtained from the reinforcement of a building for recycling. Furthermore, the study concludes that the process of steel production through an electric arc furnace consumes less energy than the process of steel production in an oxygen furnace and therefore, generates less $CO_2$ emissions. On the other hand, the burning of textile fibers avoids producing thermal energy from traditional fuels (gas, coal, fuel oil). Therefore, the savings based on using fossil fuels through these two secondary processes are greater than the consumption involved in ELT and CR transport, as observed in E1 and E2. However, as aforementioned, using CR also has an impact on the category of ozone layer depletion, as CR production involves high-impact transport operations. And, as noted above, this transport process is directly linked to ozone layer depletion. There is a 33.54% increase between the alternatives M_REF and M_40.

### 4.3. Strength vs GWP

Aiello and Leuzzi and Benazzouk et al. define the mechanical characteristics and properties of CR admixture in mortars and concretes. Their results indicate that as the percentage of a CR aggregate increases, the mechanical properties and durability of the mortar are considerably diminished [46,47]. On the other hand, other studies determine the feasibility of incorporating CR to make prefabricated elements. Sodupe et al. evaluate the productivity of various mortar mixes with different amounts of CR for the automated production of prefabricated bricks and blocks [20]. The authors state incorporating>20% of CR aggregate is not technically feasible as it leads to excessive deformations in the products.

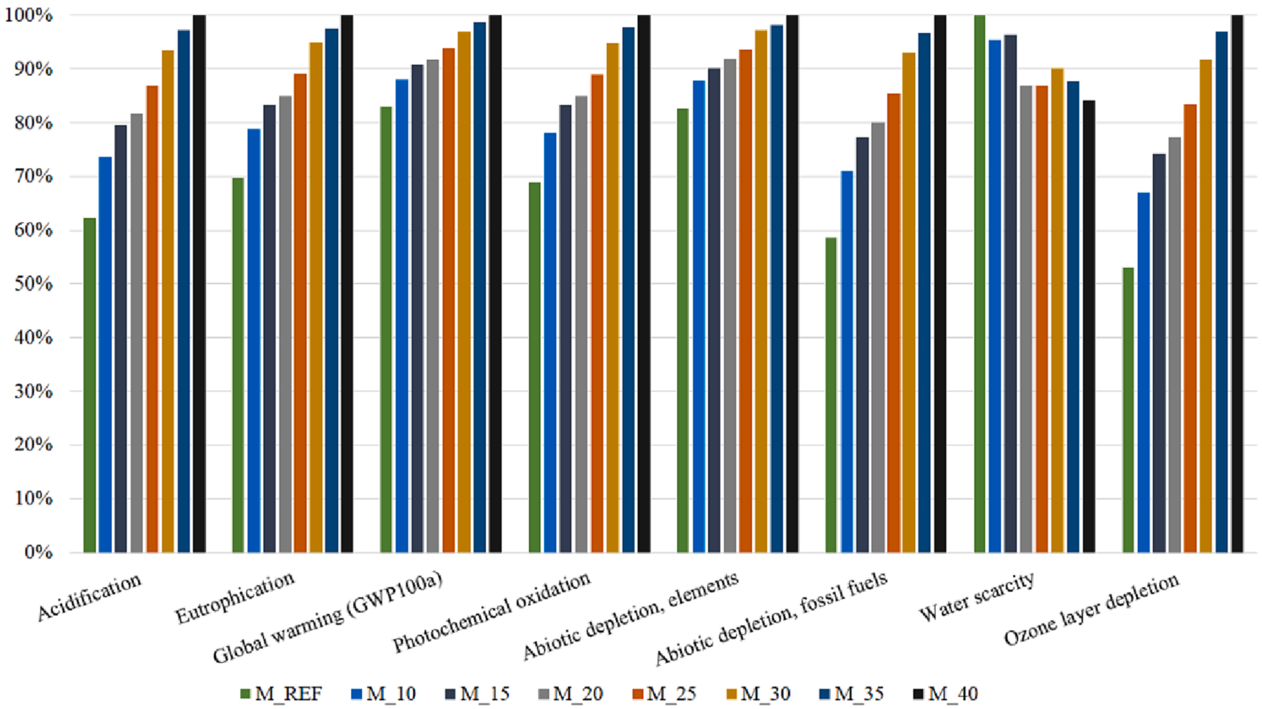

**Fig. 5.** LCA results for mortar alternatives according to EPD methodology – E2.

**Table 14**
LCA results according to EPD method - E3.

| Indicator | Unit | MREF | M10 | M15 | M20 | M25 | M30 | M35 | M40 |
|---|---|---|---|---|---|---|---|---|---|
| Acidification | kg $SO_2$ eq | 0.607 | 0.601 | 0.600 | 0.593 | 0.592 | 0.592 | 0.590 | 0.587 |
| Eutrophication | kg $PO_4$ eq | 0.0838 | 0.0875 | 0.0897 | 0.0898 | 0.0916 | 0.0942 | 0.0954 | 0.0961 |
| Global warming (GWP100a) | kg $CO_2$ eq | 270 | 240 | 226 | 217 | 204 | 188 | 178 | 170 |
| Photochemical oxidation | kg NMVOC | 0.557 | 0.458 | 0.410 | 0.379 | 0.337 | 0.286 | 0.252 | 0.225 |
| Abiotic depletion, elements | kg Sb eq | 9.27E-04 | 9.47E-04 | 9.58E-04 | 9.62E-04 | 9.71E-04 | 9.83E-04 | 9.90E-04 | 9.95E-04 |
| Abiotic depletion, fossil fuels | MJ | 1084.65 | 952 | 888 | 841 | 786 | 719 | 672 | 634 |
| Water scarcity | $m^3$ eq | 112 | 111 | 113 | 103 | 105 | 110 | 109 | 105 |
| Ozone layer depletion | kg CFC-11 eq | 1.05E-05 | 1.19E-05 | 1.28E-05 | 1.31E-05 | 1.39E-05 | 1.49E-05 | 1.54E-05 | 1.58E-05 |

Therefore, the present study of LCA results examines exclusively those alternatives containing 0–20% of CR aggregate.

Fig. 7 is a graph comparing the characteristic strength data $f_{ck}$ (MPa) at 28 days and the GWP impact category expressed in kg $CO_2$ equivalent obtained from the results of the LCA scenarios E1, E2, E3. One can be see that as the CR values increase in percentage of aggregate substitution, the characteristic strength decreases. Even for values lower than 10 MPa in the case of alternatives M_35 and M_40. This decrease in the characteristic strength makes it unviable for structural construction solutions. On the other hand, the lines of kg of $CO_2$ involved in producing 1 $m^3$ of mortar according to the defined scenarios are shown. As justified above, herein the focus is exclusively on the alternatives that would be technically feasible in the production of mortar with RC. These are M_10, M_15, M_20. It should be noted that in the case of E1 and E2 there is an increase in $CO_2$ emissions between M_REF and M_20 of 14.44% for E1, and 10.37% for E2. This increase is justified because these scenarios do not envisage any environmental benefits based on the use of the co-products produced in the ELT recycling process. On the other hand, in E3 there is a significant reduction of 19.63% in $CO_2$ kg between the alternatives M_REF and M_20. This translates to a total of 53 kg of $CO_2$.

It should be noted that environmental advantages are not only evident in the production process of mortar with CR aggregate. But, during its useful life, implementing these proportions of CR in bricks and blocks can lead to considerable energy savings in the building. Fraile et al. indicate that with a percentage of 20% CR aggregate, a variation in the temperature gradient of 2.4% can be achieved in comparison to the same material without CR aggregate [21]. Improving the thermal performance of building enclosures lowers a building's energy demands and therefore leads to less consumption of non-renewable energy and a reduction of $CO_2$ emissions.

## 5. Research uncertainty

Given the results, the environmental benefit of using CR as a fine aggregate is demonstrated. However, as stated in the introduction, the use of CR as fine aggregate would prevent ELTs from being burned for thermal energy. Having to produce the thermal energy through traditional fuels such as gas, diesel. Also, the use of CR as fine aggregate avoids its deposition in landfills without any kind of treatment. Therefore, the impacts derived from these scenarios have not been included in the results of this research through the expansion of the LCA system. This leaves a knowledge gap for future research to complement and define more specifically the environmental impacts associated with these scenarios that are generated as a consequence of using CR as fine aggregate.

## 6. Conclusions

The conclusions of this study are listed below.

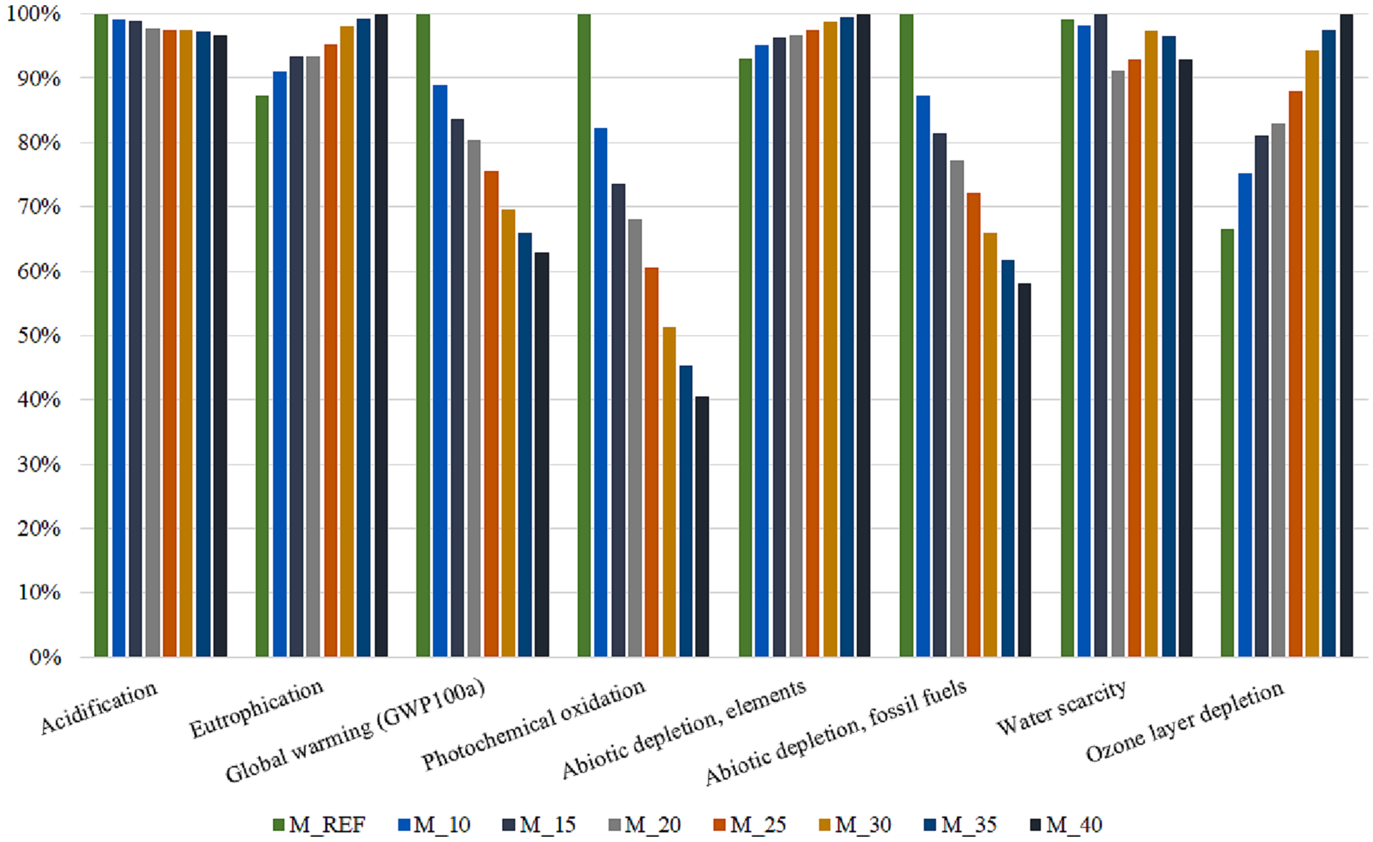

**Fig. 6.** LCA results for mortar alternative according to EPD methodology – E3.

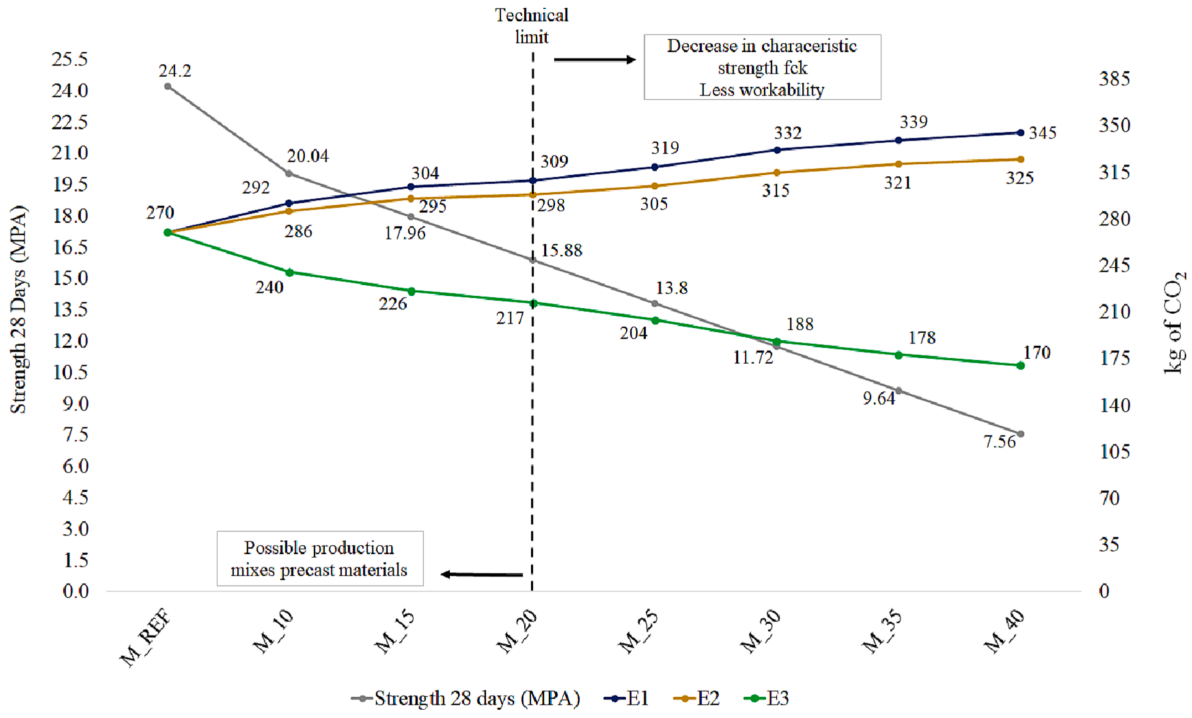

**Fig. 7.** Strength (MPa) vs GWP as a function of CR content.

- In the reference mortar, the raw material of cement is the foremost element generating environmental impacts. In the GWP category, it contributes 94.2% of $CO_2$ emissions, the remaining 5.8% deriving from the raw material processes of fine aggregate, water, and the production process itself.
- E1 is the most environmentally damaging scenario. As the amount of CR increases in each alternative, the environmental impacts also

increase. For the M_40 alternatives, there is an increase in $CO_2$ emissions of 22% for the GWP category and 49% in the ADFF category.
- In E2, impacts decline in all the categories assessed. This is due to the assignment of weight factors to each co-product obtained. This avoids directly attributing all the impacts derived from the ELT recycling process to the CR, as is the case in E1. In this way, the impacts decrease by 7% on average in all the categories as compared to E1.
- The best results were obtained in E3, thanks to modelling of the co-products scrap metal fibers and textile fibers in downstream processes, such as the production of low alloy steel and thermal energy. Henceforth, the results indicate a 37.04% reduction in GWP and 41.83% in ADFF when compared the M_REF and M_40 alternatives.
- The ozone layer depletion category is affected as increasing amounts of CR are incorporated into the mortar mix, due to the transport process. E1 is the least attractive option in this regard. There is an increase of 54% between alternative M_40 and M_REF.
- The use of environmentally viable RACs is directly dependent on the transport between the recycling plant and the mortar production plant. Transport strongly impacts fuel consumption and therefore primarily affects categories such as ozone layer depletion, ADFF, and GWP.
- The impact on the category of water scarcity decreases as the amount of CR increases in the mortar mix. The best results are obtained in E2, where there is a 16% decrease between M_REF and M_40, which is equivalent to a decrease in consumption of 17.8 $m^3$ of water. It can be concluded that the use of RACs generates savings in this category, since the production of NA implies greater water consumption.

## CRediT authorship contribution statement

**Jorge Los Santos Ortega:** Data curation, Investigation, Resources, Methodology, Validation, Visualization, Writing – original draft, Writing – review & editing. **Esteban Fraile:** Conceptualization, Data curation, Investigation, Resources, Supervision, Validation, Visualization, Methodology, Writing – original draft, Writing – review & editing. **Javier Ferreiro:** Conceptualization, Investigation, Methodology, Resources, Supervision, Validation, Visualization, Data curation, Writing – original draft, Writing – review & editing.

## 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

No data was used for the research described in the article.

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## References

[1] "Distribución porcentual de los activos por sector económico y provincia(3994)." https://www.ine.es/jaxiT3/Datos.htm?t=3994#!tabs-grafico (accessed Oct. 05, 2022).

[2] "Ocupados por sector económico y provincia(3991)." https://www.ine.es/jaxiT3/Datos.htm?t=3991 (accessed Oct. 05, 2022).

[3] E.R. Teixeira, R. Mateus, A.F. Camões, L. Bragança, F.G. Branco, Comparative environmental life-cycle analysis of concretes using biomass and coal fly ashes as partial cement replacement material, J. Clean. Prod. 112 (2016) 2221–2230, https://doi.org/10.1016/j.jclepro.2015.09.124.

[4] C. Meyer, The greening of the concrete industry, Cem. Concr. Compos. 31 (8) (Sep. 2009) 601–605, https://doi.org/10.1016/J.CEMCONCOMP.2008.12.010.

[5] CEMBUREAU, "2021 Activity Report," Brussels, May 2021. Accessed: Jan. 26, 2023. [Online]. Available: https://cembureau.eu/media/03cgodyp/2021-activity-report.pdf.

[6] F. Colangelo, A. Forcina, I. Farina, A. Petrillo, Life Cycle Assessment (LCA) of different kinds of concrete containing waste for sustainable construction, Buildings 8 (5) (2018) pp, https://doi.org/10.3390/buildings8050070.

[7] S.A. Miller, Supplementary cementitious materials to mitigate greenhouse gas emissions from concrete: can there be too much of a good thing? J. Clean Prod. 178 (Mar. 2018) 587–598, https://doi.org/10.1016/J.JCLEPRO.2018.01.008.

[8] R. Feiz, J. Ammenberg, L. Baas, M. Eklund, A. Helgstrand, R. Marshall, Improving the CO2 performance of cement, part I: utilizing life-cycle assessment and key performance indicators to assess development within the cement industry, J. Clean Prod. 98 (Jul. 2015) 272–281, https://doi.org/10.1016/J.JCLEPRO.2014.01.083.

[9] I.E. Ekop, C.J. Okeke, E.V. Inyang, "Comparative study on recycled iron filings and glass particles as a potential fine aggregate in concrete", Philos. Phenomenol. Res. Conserv. Recycl. Adv. 15 (2022) 200093.

[10] M. Etxeberria, E. Vázquez, A. Marí, M. Barra, Influence of amount of recycled coarse aggregates and production process on properties of recycled aggregate concrete, Cem. Concr. Res. 37 (5) (2007) 735–742, https://doi.org/10.1016/j.cemconres.2007.02.002.

[11] K. Celik, C. Meral, A. Petek Gursel, P.K. Mehta, A. Horvath, P.J.M. Monteiro, Mechanical properties, durability, and life-cycle assessment of self-consolidating concrete mixtures made with blended portland cements containing fly ash and limestone powder, Cem. Concr. Compos. 56 (2015) 59–72, https://doi.org/10.1016/j.cemconcomp.2014.11.003.

[12] S. Marinković, V. Radonjanin, M. Malešev, I. Ignjatović, Comparative environmental assessment of natural and recycled aggregate concrete, Waste Manag. 30 (11) (2010) 2255–2264, https://doi.org/10.1016/j.wasman.2010.04.012.

[13] R. Kurda, J.D. Silvestre, J. de Brito, Life cycle assessment of concrete made with high volume of recycled concrete aggregates and fly ash, Resour. Conserv. Recycl. 139 (2018) 407–417, https://doi.org/10.1016/j.resconrec.2018.07.004.

[14] I. Bianco, D. Panepinto, M. Zanetti, End-of-life tyres: Comparative life cycle assessment of treatment scenarios, Appl. Sci. (Switzerland) 11 (8) (2021) pp, https://doi.org/10.3390/app11083599.

[15] A. Corti, L. Lombardi, End life tyres: Alternative final disposal processes compared by LCA, Energy vol. 29, no. 12–15 SPEC (2004) 2089–2108, https://doi.org/10.1016/j.energy.2004.03.014.

[16] A. Farina, M.C. Zanetti, E. Santagata, G.A. Blengini, Life cycle assessment applied to bituminous mixtures containing recycled materials: Crumb rubber and reclaimed asphalt pavement, Resour. Conserv. Recycl. 117 (2017) 204–212, https://doi.org/10.1016/j.resconrec.2016.10.015.

[17] S. Bressi, J. Santos, M. Giunta, L. Pistonesi, D. Lo Presti, A comparative life-cycle assessment of asphalt mixtures for railway sub-ballast containing alternative materials, Resour. Conserv. Recycl. 137 (2018) 76–88, https://doi.org/10.1016/j.resconrec.2018.05.028.

[18] D. Rigotti, A. Dorigato, Novel uses of recycled rubber in civil applications, Adv. Ind. Eng. Polym. Res. 5 (4) (2022) 214–233.

[19] L. Rincón, J. Coma, G. Pérez, A. Castell, D. Boer, L.F. Cabeza, Environmental performance of recycled rubber as drainage layer in extensive green roofs. a comparative life cycle assessment, Build. Environ. 74 (2014) 22–30, https://doi.org/10.1016/j.buildenv.2014.01.001.

[20] E. Sodupe-Ortega, E. Fraile-Garcia, J. Ferreiro-Cabello, A. Sanz-Garcia, Evaluation of crumb rubber as aggregate for automated manufacturing of rubberized long hollow blocks and bricks, Constr. Build. Mater. 106 (2016) 305–316, https://doi.org/10.1016/j.conbuildmat.2015.12.131.

[21] E. Fraile-Garcia, J. Ferreiro-Cabello, M. Mendivil-Giro, A.S. Vicente-Navarro, Thermal behaviour of hollow blocks and bricks made of concrete doped with waste tyre rubber, Constr. Build. Mater. 176 (Jul. 2018) 193–200, https://doi.org/10.1016/J.CONBUILDMAT.2018.05.015.

[22] E. Fraile-Garcia, J. Ferreiro-Cabello, B. Defez, G. Peris-Fajanes, Acoustic behavior of hollow blocks and bricks made of concrete doped withwaste-tire rubber, Materials 9 (12) (2016) pp, https://doi.org/10.3390/ma9120962.

[23] R. Faizah, H. Priyosulistyo, A. Aminullah, Dynamic properties of the masonry wall structures using mortar with various brands of rubber tire cRUMBS, Xinan Jiaotong Daxue Xuebao/J. Southwest Jiaotong Univ. 57 (5) (Oct. 2022) 651–659, https://doi.org/10.35741/ISSN.0258-2724.57.5.53.

[24] A. Al-Fakih, B.S. Mohammed, M.A. Al-Osta, R. Assaggaf, Evaluation of the mechanical performance and sustainability of rubberized concrete interlocking masonry prism, J. Mater. Res. Technol. 18 (May 2022) 4385–4402, https://doi.org/10.1016/J.JMRT.2022.04.115.

[25] SIGNUS, "Memoria Anual 2021," Madrid, España, 2021. Accessed: Jan. 26, 2023. [Online]. Available: https://www.signus.es/memoria2021/inicio.

[26] “Objetivos y metas de desarrollo sostenible - Desarrollo Sostenible.” https://www.un.org/sustainabledevelopment/es/sustainable-development-goals/ (accessed Dec. 01, 2022).

[27] “UNE-EN 197-1:2011 Cemento. Parte 1: Composición, especificacio...” https://tienda.aenor.com/norma-une-en-197-1-2011-n0048623?_gl=1*shrbx3*_up*MQ..&gclid=EAIaIQobChMIm5Sq78q_-wIVQ8TVCh00NQohEAAYASAAEgJP-_D_BwE&gclsrc=aw.ds (accessed Nov. 21, 2022).

[28] UNE-EN ISO 14040. Gestión ambiental. Análisis de Ciclo de Vida. Principios y marco de referencia. Diciembre 2006.

[29] UNE-EN ISO 14044. Gestión Ambiental. Análisis de Ciclo de Vida. Requisitos y directrices. Diciembre 2006.

[30] M. De Schepper, P. Van den Heede, I. Van Driessche, N. De Belie, Life Cycle Assessment of Completely Recyclable Concrete, Materials 7 (8) (2014) 6010–6027, https://doi.org/10.3390/ma7086010.

[31] P.G. Goh, M. Maghfouri, C.C. Onn, S.C. Loo, Life cycle assessment on recycled e-waste concrete, Case Stud. Constr. Mater. 17 (2022) e01412.

[32] C. Jiménez, M. Barra, A. Josa, S. Valls, LCA of recycled and conventional concretes designed using the Equivalent Mortar Volume and classic methods, Constr. Build. Mater. 84 (2015) 245–252, https://doi.org/10.1016/j.conbuildmat.2015.03.051.

[33] C. Knoeri, E. Sanyé-Mengual, H.-J. Althaus, Comparative LCA of recycled and conventional concrete for structural applications, Int. J. Life Cycle Assess. 18 (5) (2013) 909–918, https://doi.org/10.1007/s11367-012-0544-2.

[34] N. Garcia-Troncoso, H. Baykara, M.H. Cornejo, A. Riofrio, M. Tinoco-Hidalgo, J. Flores-Rada, Comparative mechanical properties of conventional concrete mixture and concrete incorporating mining tailings sands, Case Stud. Constr. Mater. 16 (2022) e01031.

[35] Q. Tushar, J. Santos, G. Zhang, M.A. Bhuiyan, F. Giustozzi, Recycling waste vehicle tyres into crumb rubber and the transition to renewable energy sources: a comprehensive life cycle assessment, J. Environ. Manage. 323 (2022) 116289.

[36] “ecoinvent v3.0 - ecoinvent.” https://ecoinvent.org/the-ecoinvent-database/data-releases/ecoinvent-3-0/ (accessed Dec. 04, 2022).

[37] P. Van Den Heede, N. De Belie, Environmental impact and life cycle assessment (LCA) of traditional and ‘green’ concretes: Literature review and theoretical calculations, Cem. Concr. Compos. 34 (4) (Apr. 2012) 431–442, https://doi.org/10.1016/J.CEMCONCOMP.2012.01.004.

[38] M. Madrid, Y.G. Frómeta, J. Cuadrado, J.M. Blanco, Life cycle analysis in concrete blocks: comparison of the impact produced between traditional blocks and blocks made with by-products | Análisis de ciclo de vida en bloques de hormigón: comparación del impacto producido entre bloques tradicionales y con s, Informes de la Construccion 74 (566) (2022) 1–11, https://doi.org/10.3989/ic.88125.

[39] A. Yerdianti, R. Aziz, Environmental impact evaluation of crumb rubber industry production process by life cycle assessment (LCA) method (case study: PT FRP), IOP Conference Series: Earth and Environmental Science 896 (1) (2021) 012046.

[40] Z. Piao, U. Waldner, K. Heutschi, L.D. Poulikakos, S. Hellweg, Modified life cycle assessment for Low-Noise urban roads including acoustics and monetarization, Transp. Res. D Transp. Environ. 112 (Nov. 2022), 103475, https://doi.org/10.1016/J.TRD.2022.103475.

[41] “EUR-Lex - mi0029 - EN - EUR-Lex.” https://eur-lex.europa.eu/ES/legal-content/summary/emissions-from-heavy-duty-vehicles-euro-vi-certification-rules.html# (accessed Jun. 19, 2023).

[42] “Asociación Nacional de Fabricantes de Áridos - ANEFA - ANEFA.” https://www.aridos.org/ (accessed Dec. 01, 2022).

[43] P. Clemente *et al.*, “Sostenibilidad en la preparación y puesta en obra de hormigón en España: Análisis de consumo energético y emisiones de CO2,” *Proceedings from the 18th International Congress on Project Management and Engineering: (Alcañiz, July 2014), 2014, ISBN 978-84-617-2742-1, págs. 508-520*, pp. 508–520, 2014, Accessed: Dec. 01, 2022. [Online]. Available: https://dialnet.unirioja.es/servlet/articulo?codigo=8225635&info=resumen&idioma=ENG.

[44] “SIGNUS – Sistema Colectivo de Gestión de Neumáticos Fuera de Uso.” https://www.signus.es/ (accessed Dec. 01, 2022).

[45] S. Sofía, S. Silgado, X. R. Ramón, and L. C. Valdiviezo, “Una comparación del Análisis de Ciclo de Vida entre el árido reciclado y el árido natural,” *Revista EIA*, vol. 19, no. 38, p. 3801 pp. 1–15, Jun. 2022, doi: 10.24050/REIA.V19I38.1515.

[46] M.A. Aiello, F. Leuzzi, Waste tyre rubberized concrete: Properties at fresh and hardened state, Waste Manag. 30 (8–9) (Aug. 2010) 1696–1704, https://doi.org/10.1016/J.WASMAN.2010.02.005.

[47] A. Benazzouk, O. Douzane, T. Langlet, K. Mezreb, J.M. Roucoult, M. Quéneudec, Physico-mechanical properties and water absorption of cement composite containing shredded rubber wastes, Cem. Concr. Compos. 29 (10) (Nov. 2007) 732–740, https://doi.org/10.1016/J.CEMCONCOMP.2007.07.001.