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Life cycle assessment of alkali-activated cement compared to ordinary Portland cement

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1. GLOSSARY

AAC	Alkali-Activated Cement
AAM	Alkali-Activated Material
CCS	Carbon Capture and Storage
DIOPMA	<i>Centre de Disseny i Optimització de Processos i Materials</i>
EU	European Union
GWP	Global Warming Potential
IBA	Incineration Bottom Ash
LCA	Life Cycle Assessment
LCIA	Life Cycle Impact Assessment
LCI	Life Cycle Inventory
LOI	Loss On Ignition
MBT	Mechanical-Biological Treatment
MSW	Municipal Solid Waste
MSWI	Municipal Solid Waste Incinerator
OPC	Ordinary Portland Cement
SDG	Sustainable Development Goals
Sust-AAC	Sustainable-AAC
UB	<i>Universitat de Barcelona</i>
VECSA	<i>Valorización de Escorias de Combustión, SA</i>
WBA	Weathered Bottom Ash
W/C	Water and Cement paste ratio
WtE	Waste-to-Energy
XRF	X-Ray Fluorescence

2. INTRODUCTION

In the last few years, the concern about the release of carbon dioxide (CO₂) into the atmosphere has increased. This is because, society has become more aware of the impact and threats that global warming generates. Addressing this situation and reversing the effect requires strict local and international policies.

For this reason, the European Union (EU) has taken a series of measures to promote the transition towards a more sustainable society. Besides, EU is forced to reach the objectives described in international treaties, such as the 2015 Paris Agreement or the Kyoto Protocol, with increasingly demanding and ambitious environmental and energy policies. This fact is reflected in the following EU regulations, which are mandatory for all its member states:

- Directive 2018/2001 sets a mandatory target for the EU of at least 32% of renewable energy (final consumption) and a series of integrated national plans for energy and climate for 2030 [1].
- Directive 2018/2002 sets a target of 32.5% of energy efficiency, expressed in primary or final energy consumption for 2030 [2].
- Regulation (EU) 2018/1999, which obliges the Member States to develop Integrated National Energy and Climate Plans for the periods from 2021 to 2030 [3].

Approximately 8% of the global emissions of CO₂ are originated by the cement industry, which consumes on average between 4 to 6 GJ per ton of cement (2% of the global energy consumption) [4–6]. Most of the energy used is in form of fuel (from non-renewable sources) for the production of the clinker and in form of electricity to grind the raw materials and the finished cement [7,8]. The cement sector was the second-largest industrial CO₂ emitter globally and the third-largest industrial energy consumer in 2018 [5].

Ordinary Portland cement (OPC) is the most used cement for construction purposes. Every year around 4 billion tonnes (Gt) of OPC are manufactured. This value represents an annual increase of 23% compared to 2010, and 155% compared to 2000 [5]. Annual cement production is expected to grow moderately to 2030. In 2017, almost 57% of the world's cement production was produced in China, followed by India with a 6.8% and EU (Cembureau – The European Cement Association) with a 6.3% [5,9].

Currently, the production of cement has a considerable impact on the environment. For each kg of OPC produced, the amount of 0.81 kg of CO₂ is generated [10]. Two aspects of cement contribute to CO₂ emissions. On the one hand, the chemical reaction involved in the manufacturing of the main component of cement (clinker) as there carbonates' decomposition leads to CO₂ release. On the other hand, the heat needed to reach the temperature for sintering [4].

Therefore, seeking a cement with a more environmentally friendly manufacture process, economically viable and socially relevant is necessary. Cement is one of the most relevant challenges for the next years. For this purpose, the scientific and technological community is looking for new materials to replace the OPC [11–13]. One of the most promising materials is the group of Alkali-Activated Materials (AAMs).

Overall, this project focuses on the research of new materials that could replace the OPC as a building material. The comparison between AAM and OPC is performed through a Life Cycle Assessment (LCA) to evaluate the energy saving and CO₂ reductions.

2.1. MUNICIPAL SOLID WASTE INCINERATOR (MSWI)

Waste's industry is the fourth largest source sector of greenhouse gas emissions, accounting for 3% of total emissions in 2017 [14,15]. Treatment of Municipal Solid Waste (MSW) is complex due to the increasing complexity of waste management. Figure 1 shows the different treatment pathways

(incineration, landfilling, recycling and composting/digestion) and the pre-treatment operations (Mechanical-Biological Treatment and sorting).

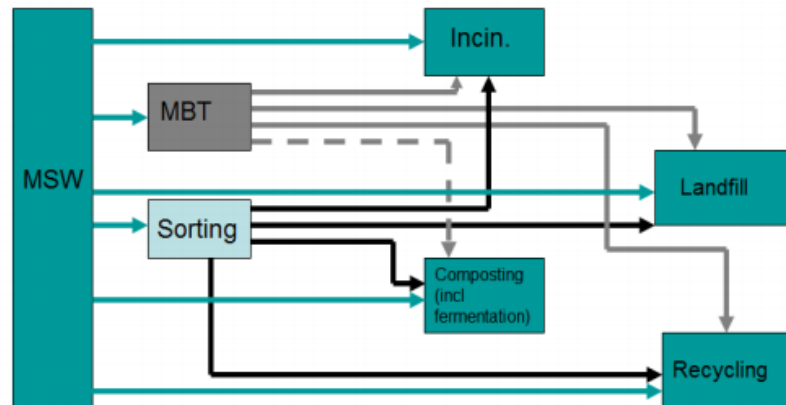


Figure 1. Municipal solid waste treatment options (extracted from [16]).

In 2017 in EU, 30% of the waste was recycled, 28% incinerated, 24% dumped in landfills and 18% composted [17]. Incineration is becoming an increasingly important treatment for energy recovery in Waste-To-Energy (WtE) plants and for the reduction of the waste to be managed, as it diminishes approximately 70% in weight and 90% in volume of MSW [6,18,19]. With the new legislative package on waste, the European Commission proposed new targets for municipal solid waste [20]:

- 65% reuse and recycling target for MSW by 2030.
- 75% reuse and recycling target for packaging waste by 2030.
- Minimum targets for reuse and recycling for specific materials contained in packaging waste.
- Maximum 10% municipal waste dump out of the total amount of MSW and a ban on the disposal of waste collected separately.

These targets are included in [21]:

- Directive 2008/98/EC on waste.
- Directive 1999/31/EC on the landfill of waste.
- Directive 94/62/EC on packaging and packaging waste.

Figure 2 shows the change in the trend of MSW treatment due to the new EU legislation [14,15]. Between 1995 and 2017, the amount of waste dumped in landfills decreased by 60% wt., the amount of waste recycled tripled and the amount of waste incinerated doubled. Changing waste treatment is an example of the progression towards a circular economy in order to gradually mitigate climate change. To understand the magnitude of this change the generation of waste in the EU must be considered. Each person in the EU generates around 478 kg of waste per year (2017) [17]. Considering the above-mentioned, research is necessary to give a second life to waste.

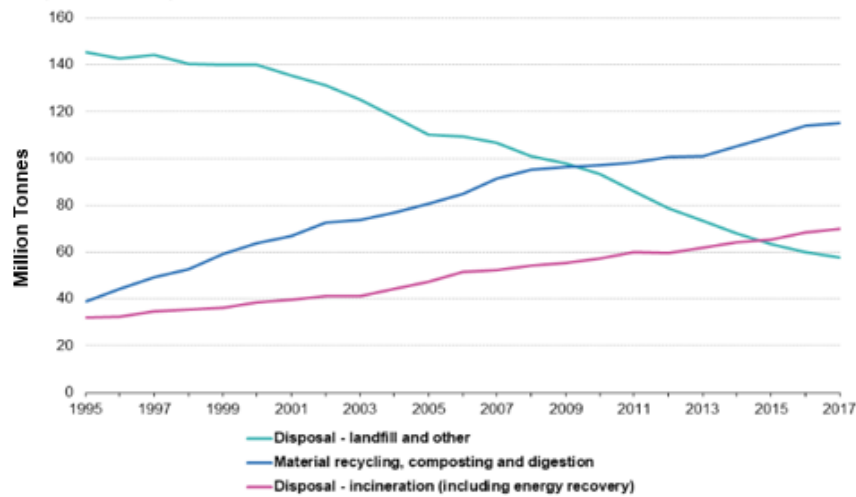


Figure 2. Municipal solid waste treatment, EU-28, 1995-2017 (extracted from [14]).

In 2016, there were 512 incineration plants in Europe [20]. Annually in Europe, incineration plants treat almost 80 million tonnes of MSW and generate energy; about 31 million MWh of electricity and 78 million MWh of heat [22]. Depending on the geographical area, climatic conditions and local legislations, the incinerator can recover only electrical energy, only heat or both if the plants operate in combined heat and power [23].

Incineration Bottom Ash (IBA) comprise the primary form of solid products and 80% wt. of total waste material remaining following incineration [24]. In 2017 19 million tonnes of IBA were generated in Europe [25]. IBA is mainly composed of silicon, calcium, iron, aluminium, and sodium, although it also contains small amounts of several heavy metals. IBA is stabilized outdoors to obtain Weathered Bottom Ash (WBA). WBAs are currently used as secondary material in construction and civil works [25]. WBA is used as raw material in this project in order to obtain an AAC (see Figure 3). The aim is to use this AAC formulated with WBA as raw material for the construction sector. In this manner, it would be possible to give a second life to this waste, thus favouring the transition to a circular economy

The Sustainable Development Goals (SDGs) are a global agenda adopted by United Nations consisting of 17 goals to be achieved by 2030. Global actions in different areas are planned in this agenda; some of these goals refer to sustainable cities or responsible production/consumption, among others. It is for this reason, that the alternative proposed in this study can help achieve OSD and other environmental regulations (local and international).

2.2. ALKALI-ACTIVATED CEMENTS (AAC)

The alkali-activated materials are considered as sustainable materials and may have the potential to replace OPC. One of the potential purposes of AAM is to be used as a binder. In that case, the AAM is considered as an Alkali-Activated Cement (AAC). AAC advantages in comparison to OPC are as follows [26]:

- Reduce emissions of greenhouse gases.
- Low energy consumption.
- High resistance and good durability compared to OPC.
- No exhaustion of mineral reserves.
- Waste recovery.

The components of AAM are (Figure 3) [8,26,27]:

- An **aluminosilicate precursor** mainly from muds and clays thermal treated (i.e. metakaolin) [8]. The present work is focused on the reduction of CO₂ emissions and saving energy. In this manner, the aluminosilicate precursor used is a waste. The precursor used in this work is Weathered Bottom Ash (WBA) obtained from the Municipal Solid Waste Incinerator (MSWI) [28].
- **Alkaline activator**. The objective of this material (usually liquid) is to accelerate the solubilisation of the aluminosilicates from the precursor, promoting the formation of stable hydrates or low solubility reaction products and promote the formation of a compact structure with the reaction products. In this project, sodium hydroxide (NaOH) and sodium silicate (Na₂SiO₃) are used as alkaline activator. Both are commercial products.

It should be noted that in the case of using WBA as precursor instead of pure raw materials, the AAC obtained is improved from a sustainable point of view. For this reason, in the following sections the AAC formulated with WBA is named Sustainable-AAC (Sust-AAC).

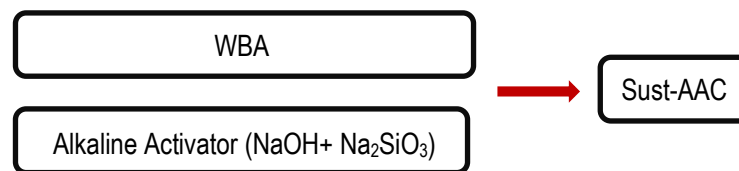


Figure 3. Preparation of Sust-AAC.

The reaction of a solid aluminosilicate with a highly concentrated aqueous alkali hydroxide and silicate solution produces a synthetic alkali aluminosilicate material generically called a geopolymer or inorganic polymer. The formation of AAC is based mainly on five steps as shown in Figure 4 [26,29]:

1. The dissolution of the solid particles by alkaline hydrolysis produces aluminate and silicate species.
2. Speciation equilibria in the solution, such as silicates, aluminates and aluminosilicates.
3. Gelation: the dissolution of amorphous aluminosilicates is rapid at high pH, and this quickly creates a supersaturated aluminosilicate solution. In concentrated solutions, this results in the formation of a gel. The time for the supersaturated aluminosilicate solution to form a continuous gel varies considerably with raw materials processing conditions and solution composition and synthesis conditions.
4. Reorganization as the connectivity of the gel rises, resulting in the three-dimensional aluminosilicate network.
5. Polymerization, in which the nucleation and growth steps occur.

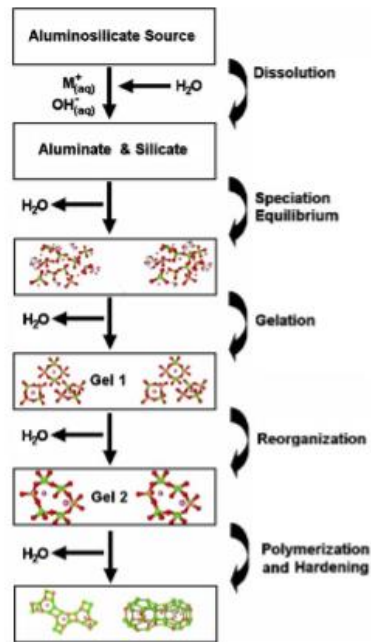


Figure 4. AAC formation (extracted from [30]).

Depending on the raw material selection and processing conditions, AAC can exhibit a wide variety of properties and characteristics, including high compressive strength, fire resistance and low thermal conductivity.

2.3. OBJECTIVES

The main purpose of this project is to perform a Life Cycle Assessment (LCA) to evaluate the environmental impacts of OPC and Sust-AAC.

The specific objectives of this study are:

- Find and determine relevant data for the study.
- Perform an exhaustive analysis of all inputs and outputs of both cements life cycle.
- Analyse the environmental impact of both cements throughout its manufacturing life.
- Evaluate different types of cement for reducing its environmental impact.

3. METHODOLOGY

In this project, a Life Cycle Assessment (LCA) is performed considering Sust-AAC and OPC. For this reason, the manufacturing process is explained in detail in the following sections.

3.1. SUSTAINABLE ALKALI-ACTIVATED CEMENT

The AAC selected for this study is related to a PhD Thesis conducted by A. Maldonado-Alameda in the research group DIOPMA. The PhD is related to the development of AACs by using WBA among other objectives. The formulation presented in this section follows Mr. Maldonado-Alameda procedure and methodology. As it was previously explained, the AAC obtained is considered as Sust-AAC.

3.1.1. RAW MATERIALS

3.1.1.1. Weathered Bottom Ash (WBA)

The company VECSA located in Tarragona, during February 2018, provided the WBA used in this project. Chemical composition of the WBA was determined by means of X-Ray Fluorescence (XRF), as it is shown in Table 1. It is important to know the date of collection of the sample since depending on the season the composition may vary, although the main components are always SiO_2 , Al_2O_3 and CaO .

Table 1. XRF of WBA from VECSA.

Compounds	WBA (wt. %)
SiO_2	45.44
CaO	17.55
Al_2O_3	10.38
Fe_2O_3	6.08
Na_2O	5.04
MgO	2.66
K_2O	1.54
P_2O_5	1.26
TiO_2	0.65
MnO	0.08
LOI	9.32

In VECSA, Incineration Bottom Ash (IBA) is separated by size with different techniques in order to recover the ferrous and non-ferrous metals from the unburned slag. Subsequently, all slag that has not been separated is transported in an outdoor storage area during 2-3 months for chemical stabilization. This process is responsible for lowering the pH to a neutral pH and it is called maturation. In this manner, the waste is carbonated and transformed into a by-product, called Weathered Bottom Ash (WBA). As it can be seen in Figure 5, WBA is a granular material of different size, i.e. $\varnothing = 0-32$ mm [31]. In this project, the entire fraction of WBA is used.



Figure 5. Weathered Bottom Ash February 2018.

3.1.1.2. Alkaline Activator

The alkaline activator used in this study for obtaining Sust-AAC is a combination of sodium hydroxide (NaOH) and sodium silicate (Na_2SiO_3) with a ratio of 0.8/0.2 (NaOH/ Na_2SiO_3). It should be considered that the type and concentration of the alkaline solution affect the dissolution of WBA.

The sodium silicate used is from the Scharlau brand and the sodium hydroxide is from company VWR Chemicals. The concentration of sodium hydroxide used has been determined through previous work. The most suitable concentration is 6M, which presents the best workability and mechanical properties. Both alkaline activators are commercial products.

3.1.2. RAW MATERIALS PREPARATION

This section describes in detail all the steps needed to prepare the raw materials. The conditions and the methodology have always been the same, as a previously developed protocol is followed to avoid experimental error in the final properties of the material.

3.1.2.1. WBA preparation

The steps to prepare the WBA are as follows:

1. **Dry** at a temperature of 105°C for 24 hours to remove humidity.
2. **Quartering method** is performed to obtain a representative sample of an adequate volume (Figure 6).

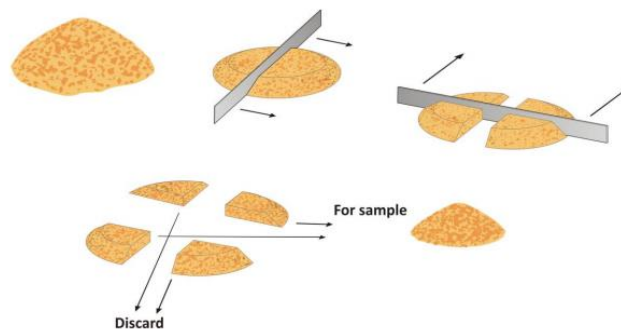


Figure 6. Quartering method (extracted from [32]).

3. **Crush** with a RETSCH crusher to obtain a homogeneous sample.

4. **Grind** with a ball mill to a fine powder below 80 μm (Figure 7). The sieve used is the RETSCH Vibratory Sieve Shaker AS 200.



Figure 7. Fine powder below 80 μm .

3.1.3. PREPARATION OF THE CEMENT

As it was aforementioned, the Sust-AAC formulation used in the present work is the result of a PhD thesis carried out by Mr. Maldonado-Alameda in DIOPMA research group of UB. Considering Mr. Maldonado-Alameda's knowledge and his previous experimental results a mixture proportions for formulating Sust-AAC was selected (Figure 8) as it is shown in Table 2.

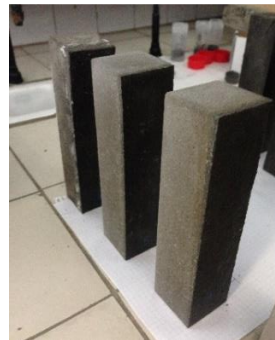


Figure 8. Sust-AAC.

Table 2. Mixture proportions for formulating Sust-AAC.

Liquid/Liquid (wt. %)		Solid/Liquid (wt. %)	
Na ₂ SiO ₃	NaOH 6M	WBA	Na ₂ SiO ₃ /NaOH
80	20	50	50

As previously mentioned, a protocol has been developed to work with the same conditions and methodology throughout the study in order to reduce the changes in variables that directly affect the properties of the final material.

First, mix the liquid solution of Na₂SiO₃/NaOH with the RW16 basic IKA[®]-WERKE equipment, the ratio always is 0.8/0.2 (NaOH/ Na₂SiO₃) as shown in Table 2. Second, WBA is added and mixed at the same speed, the liquid/solid ratio used is 1 (Table 2). The paste is introduced into the moulds and certain hits are performed to remove the inner porosity. Finally, the sample is introduced into the climate chamber for 28 days at temperature of 25°C and humidity of 95%. This chamber is used to simulate the conditions under which the commercial OPC is made.

3.2. PORTLAND CEMENT

3.2.1. RAW MATERIALS

Cement is a hydraulic binding material used in building and civil engineering construction; it is a fine powdery substance. When it is mixed with water sets as a hard mass as a consequence of the hydration products formed. Cement is a key ingredient in concrete and mortar [33,34]:

- Concrete is formed when cement mixed with water, sand and gravels with certain proportions.
- Mortar is formed when cement is mixed with water, sand and/or lime with certain proportions.

The most commonly used cement nowadays is hydraulic cement known as Ordinary Portland Cement (OPC). OPC is a powder that hydrates when mixed with water [35]. The raw components used in the manufacture of OPC are calcium oxide, silicon oxide, iron oxide and aluminium oxide [36]. These components are found in different common minerals, the most common rock types used in cement production are:

- Limestone (supplies the bulk of the lime).
- Clay, marl, chalk or shale (supplies the bulk of the silica, alumina and ferric oxide).
- Other supplementary materials such as sand and ironstone to achieve the desired composition.

These minerals or mineral ores can be used to produce OPC; but they must be used with the precise proportions. Therefore, is necessary to select a mixture with a high percentage of lime and with lower proportions of alumina, silica and iron oxide. The raw material for OPC manufacture is a rock mixture of limestone and clay or shale.

3.2.2. MANUFACTURING PROCESS

The manufacturing process of OPC is shown in Figure 9:

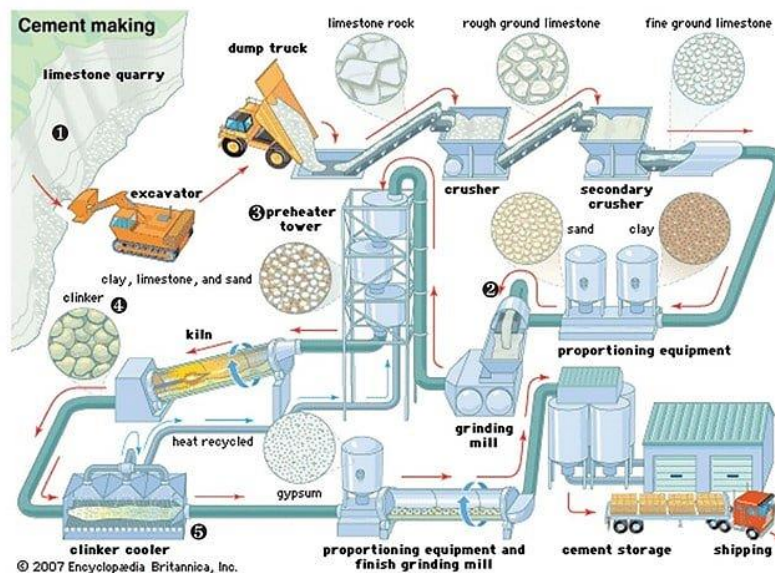


Figure 9. OPC manufacturing process (extracted from [37]).

1. Extraction

Minerals are extracted/recovered and transported to the cement plant. Limestone is taken from a quarry (major proportions), and smaller proportions of sand and clay are also needed to obtain the essential elements.

2. Crushing and milling

The raw materials are ground and milled into a fine powder. The grinding of the raw materials aims to reduce the size so that they can react chemically during clinkering.

3. Mixing of raw material

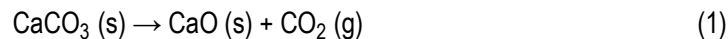
The mixing procedure of the manufacture of cement can be performed by 2 different methods (dry or wet). In the wet process the minerals are moistened by adding water to form a slurry and later dried. In the dry process, minerals are dry to form a powder-like substance.

The materials must be as homogenous as possible with the same chemical composition.

4. Burning and cooling

Hot exhaust gases coming from the kiln preheat the powdered before it enters the kiln. Later on, this mixture is introduced into the kiln (rotating cylindrical furnace), where it reaches a temperature of 1400-1500°C in order to calcine it. Once this temperature is reached, a series of chemical reactions lead to the formation of the clinker.

When calcined, calcium carbonates are transformed into calcium oxide and carbon dioxide, as indicated in Eq.1. This process is responsible for most of the cement plant emissions.



The remaining emissions are due to fossil fuels combustion, which are used to obtain the energy needed to heat the materials in the kiln [38].

5. Cooling

Clinker is extracted from the kiln and cooled with forced air to a temperature below 150°C [39]. Coolers are essential for the creation of the clinker minerals, which define the performance of the cement. Usually, 1 ton of clinker is produced from 1.6-1.8 tons of raw material [40].

6. Final grinding

The clinker, compounded of calcium oxide (CaO), silica (SiO₂), alumina (Al₂O₃) and iron oxide (Fe₂O₃), is straightaway milled with gypsum so that it can be converted into commercial OPC [11].

European standard EN 197-1 Cement talks about the composition, specifications, and conformity criteria for common cement [41]. It defines 27 distinct common cement products and their constituents. These can be grouped into five categories [33,42,43]:

- CEM I Portland cement (>95% clinker).
- CEM II Portland-composite cement (65-94% clinker, and 6-35% other constituents).
- CEM III Blast-furnace cement (5-64% clinker, and 36-95% blast-furnace slag).
- CEM IV Pozzolan cement (45-89% clinker, and 11-55% of silica fume or, pozzolana or fly ash or a combination).
- CEM V Composite cement (20-64% clinker, and 18-50% blast-furnace slag, and 18-50% pozzolana or siliceous fly ash or a combination).

In this work, the cement considered is CEM I Portland cement, which has more than 95% of clinker (Figure 10). CEM I is used for structures, pavements and products (block, tubes) among others [44]. Besides, CEM I is usually used in precast concrete industry because of the rapid setting and high mechanical properties.



Figure 10. CEM I (extracted from [45]).

The cement production was 4.1 Gt globally in 2018. In 2016, the production of cement was 163 Mt in EU (136 Mt of OPC) [46]. As previously mentioned, the cement manufacture is an intensive process in terms of energy, greenhouse gas emissions and materials [47]. In order to reduce the environmental footprint of OPC, the cement industry must make an effort to orient the sector towards [33,34]:

- Reduce demand, adopting efficiency strategies to optimize the production/use of cement.
- Reduce CO₂ (especially in the calcination process).
- New technologies for capture CO₂.
- Use alternative fuels with low-carbon technologies or renewable energies.
- Innovative processes.
- Several alternative materials more efficient and more environmentally friendly for construction.

4. LIFE CYCLE ASSESSMENT (LCA)

LCA allows to quantify the environmental impacts associated with a certain product and/or process. Going through the different stages of the product, identifying and quantifying energy and raw material consumptions as well as CO₂ emissions.

In this project, alkali-activated cement is compared with ordinary Portland cement. LCA follows ISO 14040 series, which describes the LCA in the following 4 process phases (Figure 11) [48–50]:

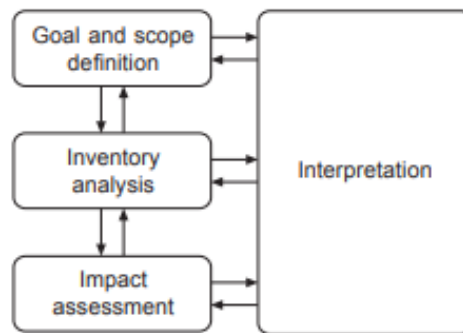


Figure 11. LCA methodology (extracted from [51]).

1. Definition of the goal and scope.

Define and describe the product and establish the context of the study.

2. Life Cycle Inventory analysis (LCI).

Includes identification and quantification of inputs (consumption of resources) and outputs (emissions, water and waste) of a set of processes for product system.

3. Life Cycle Impact Assessment (LCIA).

Assess the possible human and ecological effects of energy, water, the use of materials and the environmental emissions identified in the inventory analysis.

4. Interpretation.

Evaluate the results of the inventory and impact analysis to reach a conclusion.

Figure 12 illustrates the main lifecycle stages to be considered in LCA:

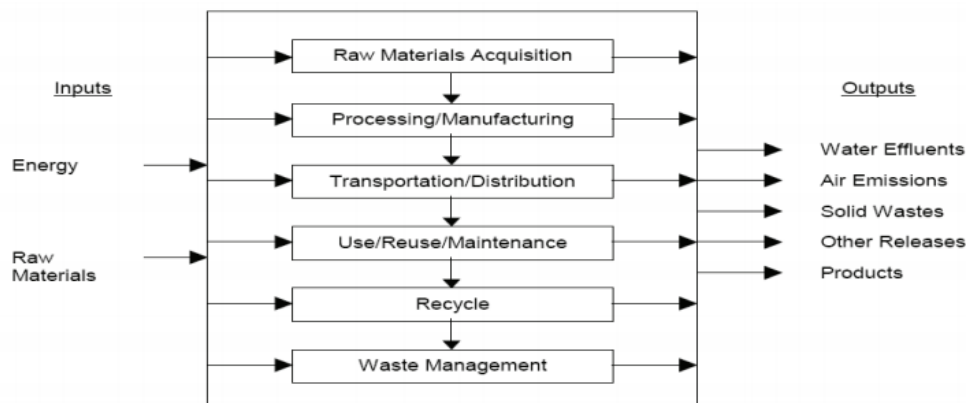


Figure 12. The main stages and typical inflows/outflows (extracted from [52]).

The product requires inputs of some raw material and energy at all stages, from acquisition to end of life. All the steps produce atmospheric emissions and water effluents among others, as the conversion never is

100%. In conclusion, the LCA provides a complete view of environmental aspects of the product and a more accurate view of the environmental benefits and drawbacks of the selected product.

This tool is essential in order to achieve the goals set by the European Union. These goals want to promote the transition from a linear economy to a circular economy with products that have a longer lifetime and are more environmentally friendly.

Globally, civil engineering works and construction consume 60% of the raw materials extracted from the lithosphere; 24% of this 60% represents the edification [53]. For this reason, the selection of building materials is completely related to the environmental impact, which is why it is necessary to study which materials are most suitable to incorporate in the building sector. However, another important property to consider is thermal insulation to save energy during the lifetime of the building. Therefore, it is important to contemplate this property when looking for eco-efficient materials for construction of buildings. LCA can help to find alternative materials with lower impact.

4.1. DEFINITION OF THE GOAL AND SCOPE

The goal of this study is to assess the environmental impacts of Sust-AAC and OPC and compare the results to evaluate which cement is more sustainable. The LCA considers from the acquisition of the raw materials to the obtaining of the final product. The scope of the LCA is based on the main production processes (raw material acquisition, processing, and product manufacturing stages).

The system boundary of this project is cradle-to-gate, which means that only from raw material extraction to the factory gate is considered. For this reason, in this project the transport, the use and disposal stages are not examined.

As shown in the previous sections, the raw materials are completely different, so during the manufacturing process of these types of cements the quantities, and the energy flow varies significantly. The material and process flow diagrams show the material/energy/heat/water consumption in each stage.

The functional unit of the assessment used in this project is 1 ton of commercial cement. Besides the water required for its manufacture it is considered. The inventories of OPC manufacture depend on the countries, the technologies of study and the mineral used as raw material. And in the case of the WBA, it also depends on the season of the year, the region, the customs and the different technologies among other factors. Because of this, it is interesting to know that there are factors that affect the outcome.

The cements studied must have a similar order of magnitude in terms of compressive strength. The Sust-AAC has a compressive strength after 28 days of curing at room temperature of 6.7 MPa [31]. Concerning OPC, diversity of studies showed that the ratio of water and cement paste (W/C) directly affects the mechanical properties; the greater this ratio the less compressive strength [54–57]. For these reasons, a W/C ratio of 0.8 has been chosen, in order to obtain a compressive strength value for OPC at 28 days as closer as possible to Sust-AAC (i.e. 20 MPa with W/C ratio of 0.8) [54].

4.2. LIFE CYCLE INVENTORY ANALYSIS

Inventories vary among depending by region, policies, available technologies, and raw materials. The OPC inventory is carried out through the values obtained in GaBi Software (software for performing LCA). However, the results have also been contrasted with different scientific papers.

The Sust-AAC inventory is made from the previous study in the research group DIOPMA. This has been developed on a laboratory scale, so it must be borne in mind that it is a hypothesis, as there is no prior inventory. Despite this, two scenarios have been taken into account when making the inventory, the

manufacture of commercial cement and the manufacture of precast cement. On the one hand, bag or big bag of commercial cement is considered. In this case, commercial cement is prepared *in-situ*. On the other hand, precast cement is factory-made cement ready to be installed directly with a desired shape (similar to precast concrete), which is prepared in a factory. During its manufacturing process the cement paste is poured into the moulds for further hardening; all processes are controlled.

4.2.1. COMMERCIAL CEMENT

The reason for considering two possible scenarios is to be able to have a wider range of results. Figure 13 and Figure 14 show the material flows from commercial cement production; the stages of the material acquisition, processing and manufacturing are considered in the life cycle inventory.

In the case of production of OPC (Figure 13), the use of 4 raw materials is observed (calcium oxides, aluminium oxides, silica and ferrous oxides), the material with a higher percentage is the CaO. The quantities of these raw materials are chosen to get the chemical balance of the desired amount of material (1 ton of commercial OPC).

These raw materials are then crushed, ground, and mixed before entering to the kiln at a high temperature, the loss of mass of 41% after calcination is due to the loss of water vapour and CO₂. The last process to form OPC is the addition of gypsum.

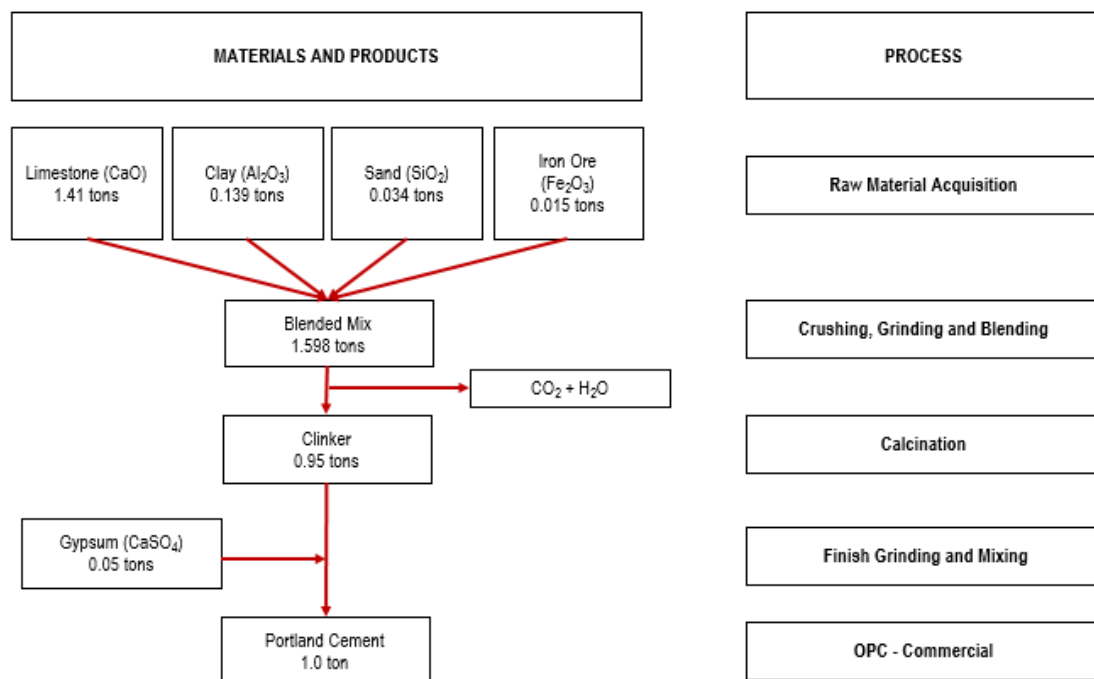


Figure 13. Material flow diagram for the production of 1 ton of OPC (commercial) (adapted from [10]).

In the case of Sust-AAC (Figure 14) the 3 raw materials do not have the same treatment processes. The raw materials with the highest percentage are WBA and sodium silicate.

The material flow of Sust-AAC shows that the first step is to dry, crush, ground and sift the WBA to obtain a fine powder below 80 μm. The loss of mass in this stage is because there is metal in the WBA that does not pass through the sieve (12.65%). The second step is to mix one of the two alkaline activators (NaOH) with the precursor. Finally, Sust-AAC is marketed with a pack of this solid mixture (precursor and sodium hydroxide) and a bottle of sodium silicate.

In order to know the exact amounts of the Sust-AAC, it must be borne in mind that in the previous study, the proportions were as follows:

- 50% precursor: 120 g of WBA.
- 50% alkaline activators: 80% is Na_2SiO_3 (96 g) and 20% is the 6M NaOH solution (24 g).

To calculate the mass of NaOH in the solution, the following conversion factors are performed:

$$\text{NaOH cm}^3 = 24\text{g NaOH 6M} * \frac{1 \text{ cm}^3}{2.13 \text{ g NaOH}} = 11.3 \text{ cm}^3$$

$$\text{NaOH (s)} = 11.3 \text{ ml} * \frac{6 \text{ mol NaOH}}{1\text{L}} * \frac{1\text{L}}{1000 \text{ ml}} * \frac{39.997 \text{ g NaOH}}{1 \text{ mol NaOH}} = 2.71 \text{ g NaOH (s)}$$

Therefore, of the 24 g of 6M NaOH solution, 2.71 g are solid pearls of NaOH (11.29%) and 21.28 g are water (88.71%). With this relationship, the values can be extrapolated to obtain the desired functional unit.

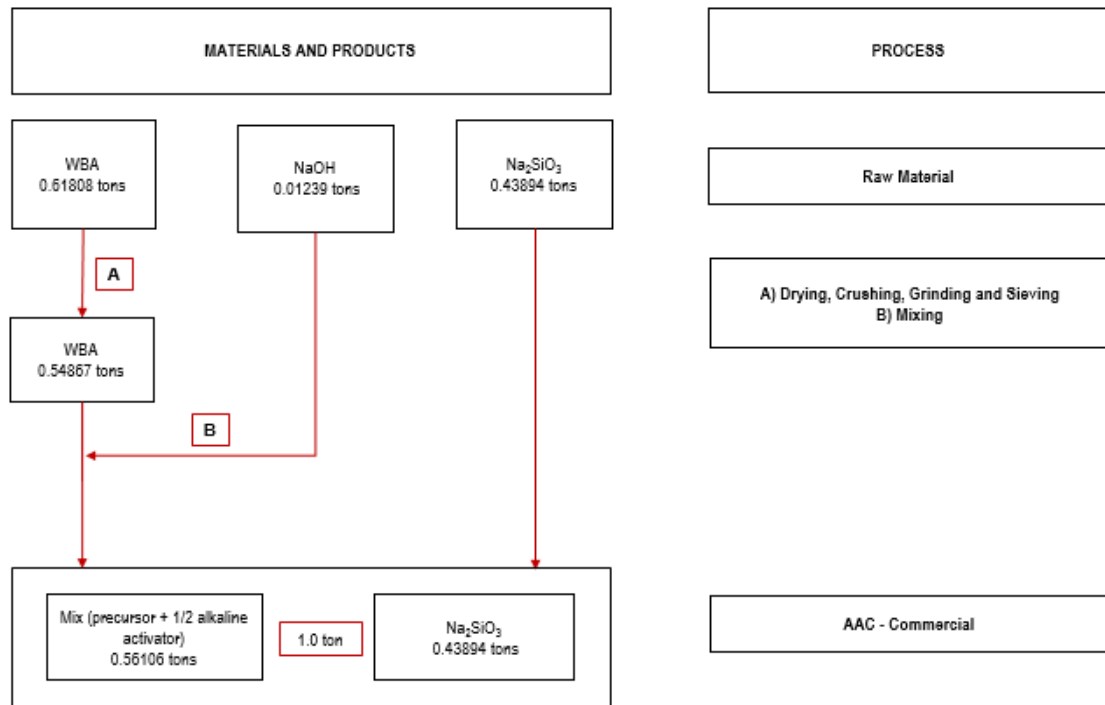


Figure 14. Material flow diagram for the production of 1 ton of Sust-AAC (commercial).

The process flow diagrams consider the particulate emissions, the gaseous emissions, the energy and heat required. However, the use of water also has been considered. Figure 15 shows that the process of OPC is completely different from that of Sust-AAC (Figure 16) because the raw material treatment processes are not the same.

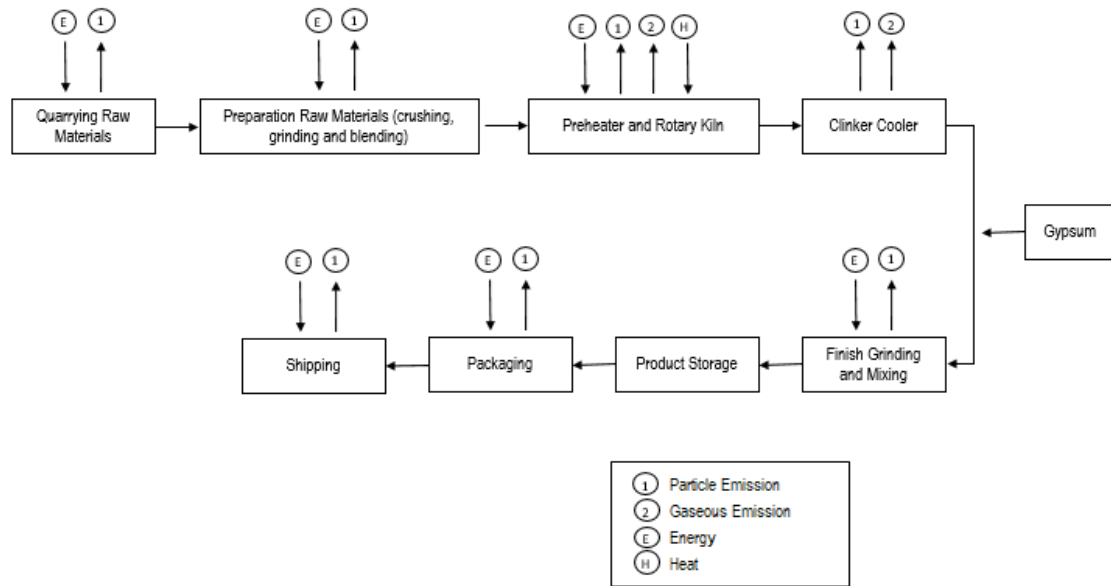


Figure 15. Process flow diagram for the manufacturing process of OPC (commercial) (adapted from [10]).

In the Sust-AAC the aluminosilicate precursor is the waste resulting from incinerator municipal solid waste; these wastes are significant because provide an environmental and economic cost reduction. Therefore, the impacts of the processes of WBA obtaining from MSW are not considered. Only the processes directly linked to the preparation of the WBA to its use as a precursor are considered. This can be seen reflected in Figure 16.

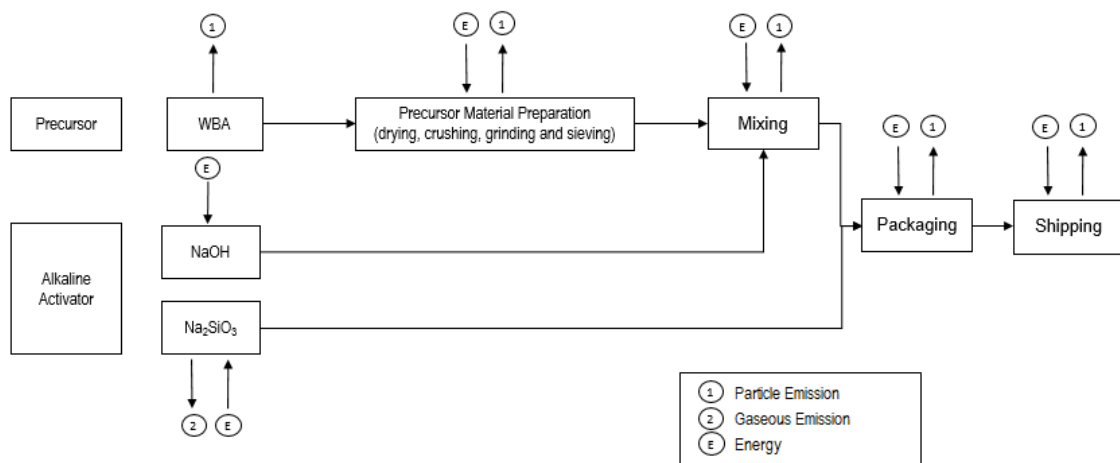


Figure 16. Process flow diagram for the manufacturing process of Sust-AAC (commercial).

4.2.2. PRECAST CEMENT

Figure 17 and Figure 18 show the material flow for producing precast cement (cement paste). The functional units are the same as in the previous section, but here the addition of water is also considered.

The reason for studying the impact of precast cements is because CEM I is a cement suitable for marketing as precast cement and the Sust-AAC has been carried out in the laboratory as precast cement. It should be noted that NaOH (alkaline activator) is irritating and can cause burns on the skin of the workers, so it is strictly necessary to make good use of it to ensure the well-being of the workers. This

aspect limits the use of the Sust-AAC, as they should be marketed as precast in order to avoid possible risks.

In the case of OPC, Figure 17, the ratio of water to cement paste (W/C) affects the properties, and as mentioned above a ratio of 0.8 W/C has been chosen. As a result of this ratio, in addition to having 1 ton of OPC, 800kg of water must also be considered.

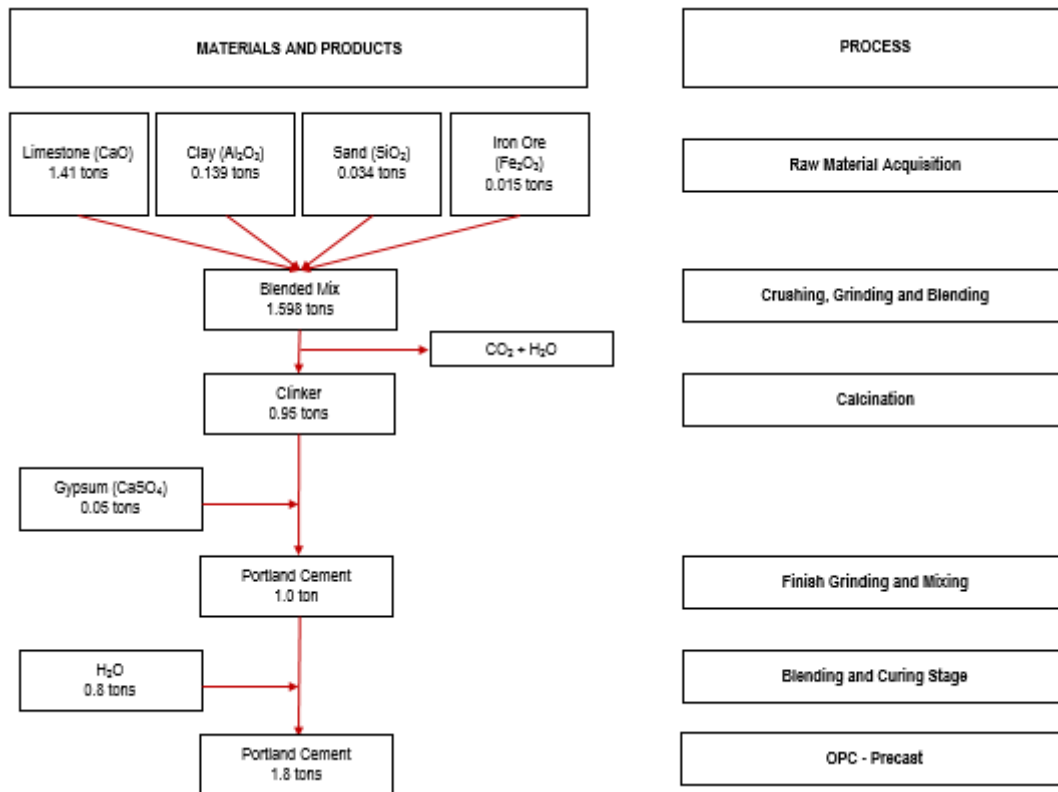


Figure 17. Material flow diagram for the production of paste OPC (precast).

For the Sust-AAC, the addition of water is also valued. In this case, the amount of water is much lower than the water used in the manufacture of OPC. Figure 18 shows the methodology performed in the study of Sust-AAC. Even so, water could also be added at the end of the manufacturing process instead of being added at the beginning, as the quantities of water would be the same and therefore the energy required, and emissions would be the same.

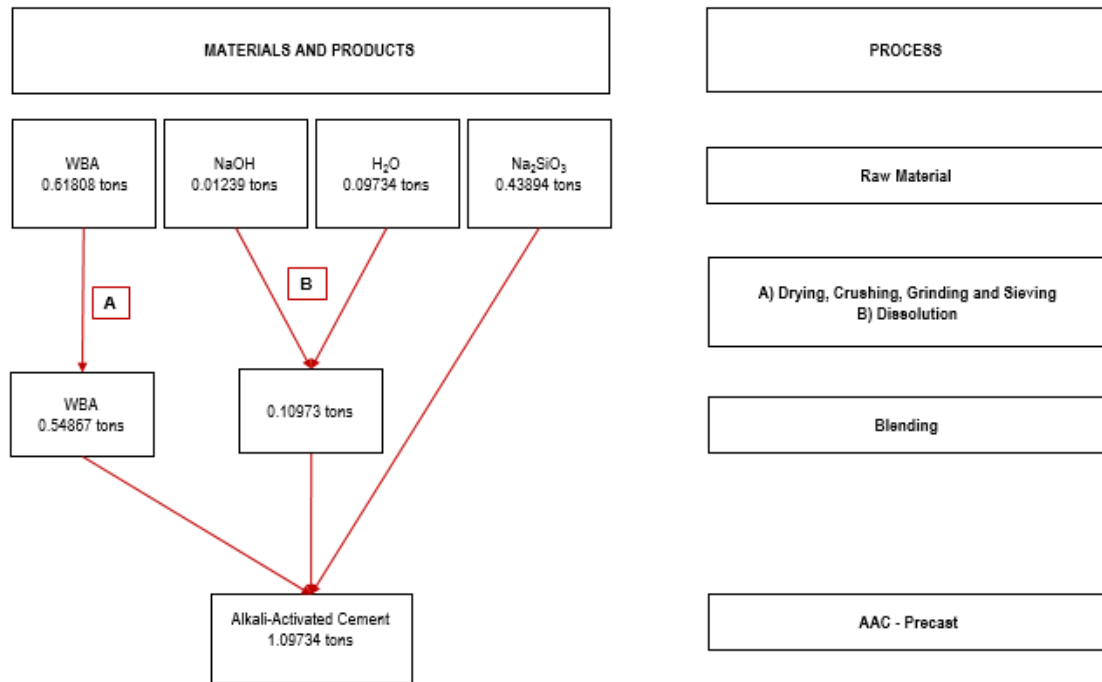


Figure 18. Material flow diagram for the production of paste Sust-AAC (precast).

Process flow diagrams for the manufacturing of precast cement (Figure 19 and Figure 20) consider the addition of water, its subsequent mixing and finally the curing stage, unlike the previous commercial cement.

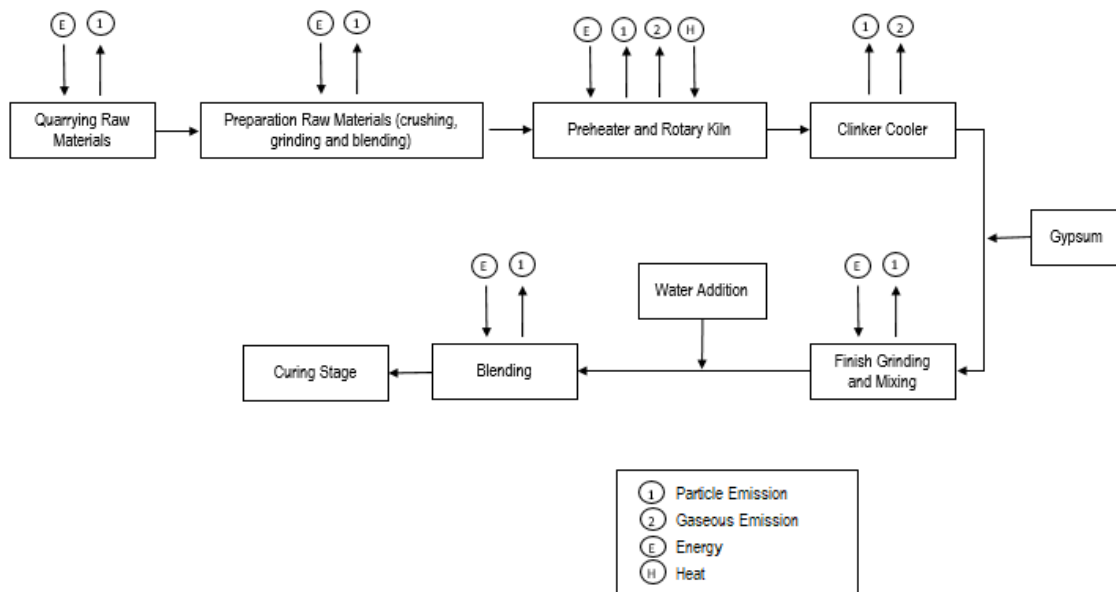


Figure 19. Process flow diagram for the manufacturing process of OPC (precast).

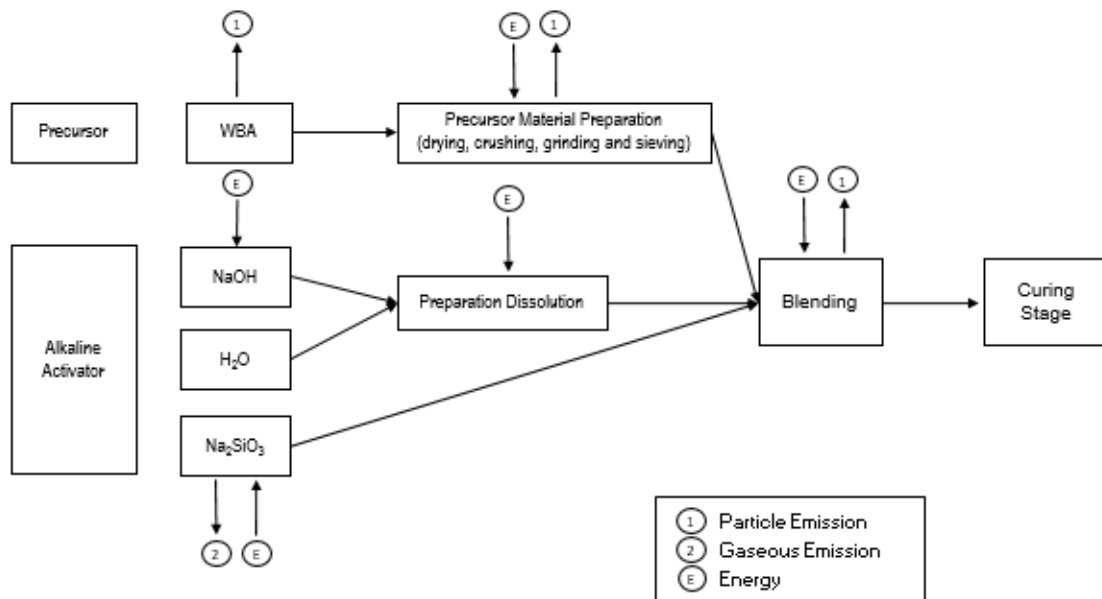


Figure 20. Process flow diagram for the manufacturing process of Sust-AAC (precast).

The detailed inventories of precast cements are shown below (Table 3 and Table 8). Only the processes and materials used to obtain 1 ton of commercial cement and the necessary quantity of water to manufacture precast cement required are considered. The processes of water addition, final mixing and curing stage have not been considered in this study.

To perform this inventory, three types of CEM I from the GaBi program database have been studied. For this reason, a range of values appears in Table 3. GaBi database provides a lot information about the environmental impacts such as the acidification potential, the ozone layer depletion potential, the human toxicity potential among others; although only greenhouse gases and energy consumption have been evaluated from this database. Table 3 shows the results of energy, CO₂ emissions and water required for manufacturing precast OPC.

Table 3. Inventory for the production of the precast OPC.

Parameter	Values
Energy Consumption (MJ)	3130-3480
CO ₂ Emissions (kg CO ₂)	834-854
Water Usage (kg)	800

The values of GaBi's database have been taken as a reference, although it should be noted that these values may vary depending on whether technologies more efficient are used, according to state regulations and according to energy sources among others.

Table 4 shows an example of the variety of values according to different reference sources from literature. These inventories are for CEM I Portland cement, they are not an inventory of the overall production of all types of Portland cement (average).

Table 4. Inventories of OPC (CEM I).

Reference	Cement Type	MJ	Kg CO ₂
[58]	Cement P	4544	355
	Cement CH	3537	810
	Cement N	4407	813
	Portland cement NL1	3698	853
	Cement S	4540	805
	Cement SF1	4350	780
	Cement SF2	5350	813
GaBi	EU-CEM:28 (CEM I 32.5)	3130	834
	EU-CEM:28 (CEM I 42.5)	3260	841
	EU-CEM:28 (CEM I 52.5)	3480	854
[10]*	Traditional Portland Cement	5396	510

*It does not take into account the extraction of raw materials.

The following tables shown an approach of energy, emissions, and water used in the Sust-AAC manufacturing process. The machinery used in the manufacture of Sust-AAC and its respective time of use are evaluated. An estimate is then made for the functional unit of this study.

Table 5 shows the estimation of energy consumption throughout the treatment process of WBA. The stage that consumes the most energy is drying in the stove [59].

Table 5. Energy consumption of Sust-AAC (treatment process of WBA).

Process	Consumption (W)	Time (h)	kWh	MJ
Drying	4000	24	96	345.6
Crushing	1100	1	1.1	3.96
Grinding	150	24	3.6	12.96
Sieving	170	6	1.02	3.67
Mixing	75	0.12	0.009	0.03
Total			101.73	366.22

To calculate the total emissions of the cement (Table 6) and the total energy consumption of the cement (Table 7), it is necessary to consider that the sodium silicate is obtained from the mixture of sodium carbonate and quartz. These products are mixed and melted with a temperature range between 1100 and 1200°C producing an amorphous solid. In this reaction, the decomposition of sodium carbonate produces CO₂ and the dissolution of the solid is transformed into an aqueous solution of sodium silicate. High temperatures are reflected in emissions and high energy demand; the estimated total emissions are 1.514 kg CO₂ per kg sodium silicate and the energy consumption is 5371 MJ per 1 ton [60,61].

The impact of sodium hydroxide depends on the production type, it is produced commercially by two basic methods: electrolytic (there are 3 typed of electrolytic cells: membrane, mercury and diaphragm) and chemical process (produced by the reaction of sodium carbonate with calcium hydroxide). The estimated total emissions are 1.915 kg CO₂ per kg NaOH and the energy consumption is 3.5 MJ per Kg NaOH; these values are considered as a reference [61,62]. NaOH's impact is lower than sodium silicate impact because sodium hydroxide is used in smaller proportions.

Table 6. CO₂ emissions of Sust-AAC.

Parameter	Values (kg CO ₂)
Energy Consumption Sust-AAC	24.52
Sodium Hydroxide	23.73
Sodium Silicate	664.56
Total	712.81

Table 7. Total energy consumption of Sust-AAC.

Parameter	Values (MJ)
Energy Consumption Sust-AAC (treatment process)	366.22
Sodium Hydroxide	43.37
Sodium Silicate	2357.55
Total	2767.14

Table 8 reveals the inventory for the production of 1 ton of commercial Sust-AAC cement, although the water needed for precasting is also taken into account. Another relevant factor is that there are also emissions of dust and other emissions to air (NO_x, SO₂, PO₄...), although they are not quantified due to the impossibility of calculation.

Table 8. Inventory for the production of 1 ton of Sust-AAC.

Parameter	Values
Energy Consumption (MJ)	2767.14
CO ₂ Emissions (kg CO ₂)	712.81
Water Usage (kg)	97.34

These inventories (Table 3 and Table 8) have been carried out to manufacture 1 ton of dry material (commercial cement), in addition to taking into account the water required to manufacture the corresponding amount of the precast cement. Another possible scenario would be to consider the same amount of final precast cement as functional unit. Hence, in this scenario the Sust-AAC inventory would change significantly (see Table 9). Another functional unit that could have been studied is 1m³ of final cement considering the fresh density of the material. Therefore, to avoid confusion and significant changes in results, it is important to properly define the functional unit.

Table 9. Inventory for the production of 1.8 tons of Sust-AAC.

Parameter	Values
Energy Consumption (GJ)	3867.56
CO ₂ Emissions (kg CO ₂)	1153.51
Water Usage (kg)	159.68

4.3. LIFE CYCLE IMPACT ASSESSMENT

Inventory's results (mass and energy inputs and outputs) are translated into environmental impact categories. The classification of the categories serves to describe the potential environmental effects of inputs and outputs, and decide what environmental impacts are considered in this assessment. The two

categories of impacts that have been reflected in this study are natural resources and ecological health. Inventory data have been assigned to the following impact categories [49,63–66]:

- Resource consumption. Impact produced by:
 - Extraction of minerals: land degradation and erosion.
 - Consumption of energy resources: energy consumed in obtaining raw materials and in the manufacture of the product.
 - Water usage: water consumed in the manufacturing process (water footprint).
- Global warming: phenomenon that shows on average an increase in temperature of the atmosphere (carbon footprint).

Table 10 shows the different impact categories and their respective indicators and units.

Table 10. Impact Categories.

Impact Categories	Category Indicators	Units
Resource consumption	Extraction of minerals	Kg (by material)
	Consumption of energy resources	MJ
	Water usage	kg H ₂ O
Global Warming Potential (GWP)	CO ₂	Kg CO ₂

4.4. INTERPRETATION

This LCA has been useful to visualize the energy, resource and emission requirements, always comparing the inputs and outputs of the studied products. Thus, using the LCA study, the possible improvements that would be made with the aim of reducing the environmental impact of the studied cements can be identified. Table 11 shows the results obtained in the previous sections.

Table 11. Inventories of OPC and Sust-AAC.

Parameter	OPC	Sust-AAC
Energy Consumption (MJ)	3130-3480 ⁽¹⁾	2767.14 ⁽²⁾
CO ₂ Emissions (kg CO ₂)	834-854 ⁽¹⁾	712.81 ⁽²⁾
Water Usage (kg)	800 ⁽²⁾	97.34 ⁽²⁾

⁽¹⁾ Extracted from GaBi Software.

⁽²⁾ Calculated.

As can be seen in Table 11, Sust-AAC presents lower energy consumption compared to OPC, about **12-20%** less. Most of the emissions and energy demand of OPC are related to the calcination process, due to the high thermal demand of this process. In a scientific paper that SimaPro (LCA software for fact-based sustainability) is used to evaluate the environmental impacts of inventory, it is observed that 86% of the required energy are for the preheating and kiln stage [67]. The remaining 14% result from the other manufacturing processes.

In contrast, in the Sust-AAC the main energy consumption is sodium silicate used as alkaline activator for the formation of Sust-AAC, which is responsible of 85% of energy consumption. In future works is mandatory to reduce the use of sodium silicate, or search a new source from industrial wastes or slags.

In terms of the carbon footprint, as shown in Table 11, the OPC releases **15-17%** more than Sust-AAC. The highest CO₂ emissions in the manufacturing of OPC (Figure 21) occur during the stage of calcination,

meanwhile in the case of Sust-AAC (Figure 22) the main contributing component related to CO₂ emissions is the production of sodium silicate [68].

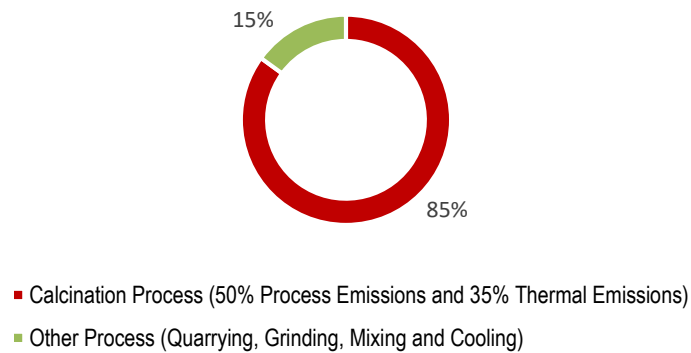


Figure 21. CO₂ emissions of OPC.

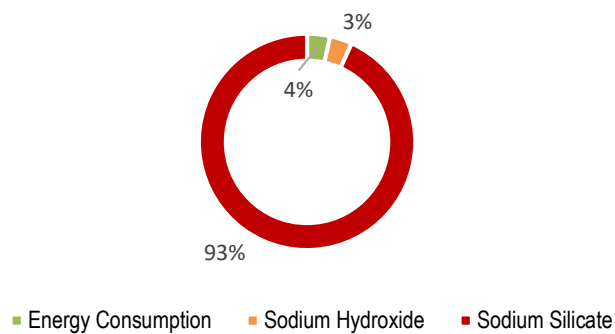


Figure 22. CO₂ emissions of Sust-AAC.

However, Table 11 shows that the OPC's water footprint is much higher compared to the water footprint of the Sust-AAC, about **88%** more. This is related to the W/C ratio considered for OPC as well as the sodium silicate and sodium hydroxide considered for Sust-AAC.

It should be considered that the raw materials used in the OPC and in the alkaline activators for the Sust-AAC (gravel/sand quarry, deposits rich in NaCl...) are the result of mineral extraction. The extraction of minerals has negative consequences for the environment such as changes in the morphology of the land, damage to flora and fauna, environmental impact, water/air pollution... The emitted gases have their origin in the combustion machinery, emissions during the extraction process, emissions in explosions, and issuances directly related to mining activity. However, the impact at the category of mineral extraction is higher in the OPC as it is used in greater quantities.

Otherwise, the Sust-AAC allows the use of the waste as a product, thus avoiding its shipment to a landfill and its environmental impacts associated with them. Besides, the use of waste implies energy/resource savings. Another relevant factor is that the WBA can be obtained locally in all those regions that have incinerator plants, while the raw materials of OPC or the alkaline activators depend on the nature of the local deposits in each region. In the case of not having local deposits, these minerals will have to be exported from other regions, assuming the environmental and economic cost of their transport.

The Sust-AAC has an equivalent compressive strength of 6.7 MPa (cured 28 days at room temperature) and the CEM I Portland cement with a ratio of 0.8 W/S has an expected compressive strength of 20 MPa

(cured 28 days at room temperature). This type of AAC does not have (at the moment) benefits at a structural level, as the OPC represents better mechanical properties.

Given these results, the Sust-AAC would be a possible candidate as a substitute for the OPC. However, it is still in the research phase to be implemented. Nowadays it still presents obstacles to its marketing due to a lack of standardization that guarantees viability and security in its properties and characteristics.

Many studies are being carried out, but more research is needed on these alternative materials in order to achieve their applicability. It should be noticed that switching from ordinary technology, to cleaner technology involves a higher investment, for this reason, policies and financial aid will be needed to make it feasible and viable.

LCA demonstrates the great potential of using Sust-AAC in order to reduce the impact as building material. However, for the reasons above mentioned, a deep research for using this cement in construction should be conducted for considering it as a viable alternative.

5. ANALYSES AND DISCUSSION

In the previous section, it was commented that the Sust-AAC of this study has lower mechanical properties than the selected OPC (0.8 W/C). If the precast Sust-AAC were cured at a higher temperature, its mechanical properties would be higher. Thus, it would be more optimal for its applicability as structural material. However, an increase in the curing temperature also implies an increase in energy demand and therefore a higher amount of energy and emissions associated with this process. Besides, if it is cured at a higher temperature, Sust-AAC can only be precast, as commercial cement is cured at room temperature. Another aspect to consider is that if the relationship between the water and the cement paste of the OPC were modified the mechanical properties would also be affected. Therefore, to obtain better mechanical properties, the W/C ratio should be lower. In this manner, the water footprint would be lower.

Another option to improve the mechanical properties of Sust-AAC would be to use the fraction larger than 8 mm of WBA. This fraction leachates less heavy metals than the whole fraction [6]. If this fraction is used, a stage should be added at the beginning of the manufacturing process of the cement, which would be the sieving stage in order to obtain the desired fraction. By using 8 mm large fraction of WBA, Mr. Maldonado-Alameda has obtained compressive strengths of around 23 MPa, so it can be observed that this AAC presents higher compressive strength in comparison to Sust-AAC (whole fraction). Despite the structural improvement, if the fraction larger than 8 mm was used, only 30% of the total of WBA would be used (Figure 23), so there would be a problem in managing the remaining 70% of the WBA. However, the remaining fraction could also be reused as aggregate for producing a sustainable concrete or mortar. This case would be considered for further studies.

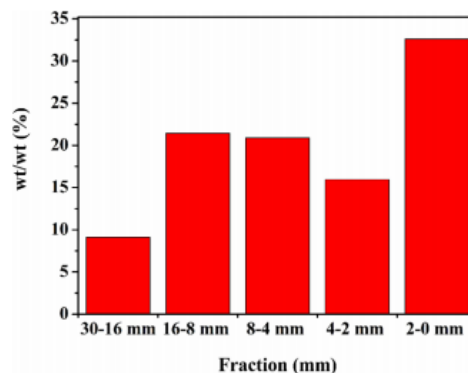


Figure 23. Particle size distribution of WBA (extracted from [6]).

The Sust-AAC has a limitation as a structural material. Despite this, there are non-structural applications where the Sust-AAC may be applicable. In Europe, about 40% of current energy consumption is due to buildings, not only during the construction process but also during its lifetime [34]. To reduce this energy consumption and CO₂ emissions the energy demand of buildings must be reduced by using passive insulation systems and materials with high thermal inertia (capacity to conserve thermal energy). Additionally, the Sust-AAC is a light material as its bulk density is 1.19 g/cm³ compared to the density of OPC, which is 2.8 g/cm³ [31]. This is because Sust-AAC presents more porosity. The mechanical properties of materials highly depend on their porosity; the porous materials are very interesting in terms of thermal and acoustic conductivity. For this reason, Sust-AAC has a possible application related to thermal insulation in the construction industry, as a lightweight binder for developing isolation panels.

Another application of Sust-AAC is to make more sustainable mortars and concretes. Prior to beginning of the state of alarm due to COVID-19, this work aimed to carry out an energy evaluation of a mortar

formulated from the whole fraction of WBA (as aggregate and binder). The aim of the mortar was to be more energy efficient and thus be able to replace the conventional mortar based on OPC.

Interest in a radical change is needed; however, the solution lies not only in the replacement of clinker as a building material, but also in technological improvement, with the implementation of more demanding policies and with more funding. There is a series of research to reduce energy consumption and emissions during the cement production process; some examples would be to increase the thermal efficiency of the facilities, use renewable energy sources, Carbon Capture and Storage (CCS)... [5]. Another way to reduce emissions, energy demand and natural resources needed would be to use new additions in the production of the cement; these additives can also improve their properties. Therefore, in addition to the alternative explained in this project (Sust-AAC), it is observed that there is a large window of possibilities.

In terms of economic aspects of the cements, in 2017 the average selling price of cement in the EU was around 60€ per tonne, although the price can vary significantly. The average of EU production costs for cement was around 48€ (range within from 35€ to 73€) [42]. One factor that may limit the application of AACs is their cost. The costs of sodium silicate (566.12 €/ton) and sodium hydroxide (884.56 €/ton) are the main factors that affect the economic viability of Sust-AAC manufacturing [69]. The production cost of 1 ton of commercial Sust-AAC taking into account the raw materials used and energy consumption (0.1199€/kWh) is 270€; this price doesn't consider either water or transportation. Currently, the price of Sust-AAC is 92% more expensive than OPC's price. In order to produce economically viable Sust-AAC other alkaline activators with a more competitive price must be found, always maintaining the required properties of the cement. Further research must be conducted in order to find wastes, by-products and residues as sodium hydroxide and/or silicate source.

Cement is locally produced and locally consumed. It is supplied within a close geographical (150-250 km), as due to its weight it would be economically unfeasible to transport it further. In terms of the geographical of cement production, in 2016 the largest EU Portland producer was Italy, Germany, France, Spain and Poland. These countries account 57% of total EU production [42]. In contrast, AAC produced with WBA can be manufactured in every country because MSW exists everywhere. The WBAs of this work are from the company SIRUSA, which incinerates 400 tons of waste every day [70]. Therefore, this data verifies that wherever there is an MSW incinerator plant there will be a considerable amount of WBA.

To understand the magnitude of saving of energy and CO₂ emissions, it is important to know that each ton of clinker emits 849 kg CO₂ (60% of process emissions and 40% of fuel emissions) and the average thermal energy consumption is 3730 MJ per ton of clinker [33]. In 2016 the European cement industry produced 111 Mt of clinker. Therefore, if in 2016 10% of the clinker has been replaced by Sust-AAC, this fact would have saved 1.5 Mt of CO₂ and 0.11 GJ [33,46]. If in the future Sust-AAC are applicable, they will have many advantages. Sust-AAC could contribute to the global targets for reducing the emissions; especially the emissions associated with the construction sector and benefit the circular economy.

In conclusion, in order to achieve the EU's targets, reducing the environmental footprint of the cement sector through alternative materials, energy efficiency and renewable energy among others is mandatory. The complete transition to a circular economy, neutral in carbon and with zero waste, must be a shared responsibility.

6. CONCLUSIONS

The main conclusions are as follows:

- The EU has set out a series of initiatives to achieve a sustainable Europe in the coming years. Cement industry poses an environmental problem as it has a considerable impact. For this reason, cement industry has focused to reduce the CO₂ emissions, developing alternative materials, reducing the clinker-to cement ratio, deploying innovative technologies and process, increasing energy efficiency and using alternative fuels (lower-carbon fuels).
- In this project, a detailed environmental evaluation of cement has been performed using the tool of LCA. The environmental impacts of 1 ton of OPC and Sust-AAC has been compared. The factors that have been assessed in the comparison of these cements are extraction of minerals, energy consumption, CO₂ emissions and water usage. However, there are limitations in the study because the Sust-AAC studied is in the experimental phase and therefore no other impacts can be evaluated due to the impossibility of getting the necessary data.
- In the manufacturing of OPC, the stage of the kiln (clinker manufacture) is the most energy intensive stage (by the chemical reaction and by the fossil fuel requirement) and therefore, has the most significant environmental impact in terms of CO₂ emissions and energy consumption. In contrast, the highest environmental impacts of Sust-AAC are due to the production of sodium silicate.
- The OPC has a higher impact in the following categories compared to Sust-AAC: global warming (**15-17%** more), energy consumption (**12-20%** more), water consumption (**88%** more) and mineral extraction. The reason for the energy saving is because Sust-AAC production does not need a kiln with high temperatures.
- The use of incinerator waste favours the return of this waste to the production cycle as raw material, promoting a circular economy. This aspect is relevant, as waste policies are becoming more stringent. Nevertheless, the use of waste also avoids the use of natural resources and the impacts associated with the extraction, conditioning and transportation of minerals. In addition, landfill disposal would be reduced.
- Despite the environmental improvement of the Sust-AAC's, in structural terms, the OPC has better compressive strength than Sust-AAC. The mechanical properties are responsible for the behaviour of a material, and for this reason, these properties are essential to ensure the quality of the building materials and are necessary to define their applicability.
- The need to limit the consumption of natural resources and lower the energy demand has led to the design of new sustainable materials, processes and technologies. Thermal insulating materials can improve the energy efficiency of buildings. Sust-AAC is suitable to be used as a lightweight material and insulation materials for thermal insulating applications. This applicability can contribute to realising operational energy savings and performance benefits.
- This project reflects the need to find a solution to the current problem, but more research on Sust-AAC is still needed to ensure its applicability. Nevertheless, these materials have the potential for the production of "green" materials with a lower carbon footprint.
- The future research of AAC will drive a new era of greener materials in the construction industry. The research must be accompanied by regulations and funding.
- In future work, sodium silicate could be substituted by sodic slags, in order to reduce the impact and contribute to sustainable development. Always bearing in mind that for future standardization they must have correct mechanical properties.

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RESUM

Actualment el canvi climàtic s'ha convertit en una de les principals amenaces mundials. En els darrers anys ha augmentat l'interès en estratègies, acords i normatives locals, estatals i internacionals per tal de fer front a la crisi climàtica i d'aquesta manera reduir les creixents conseqüències.

Aproximadament el 8% de les emissions globals de CO₂ s'originen a la indústria del ciment, i el 3% de l'energia primària global consumida prové del ciment Portland (OPC). És per aquest motiu, que tot l'entorn científic i tecnològic està cercant nous materials per a substituir el material de construcció més emprat fins ara, l'OPC, per tal de reduir la petjada ambiental del sector de la construcció. Una possible alternativa són els ciments alcalins (AAC). Aquests permeten convertir una varietat de fluxos de residus en subproductes útils. L'elaboració de l'AAC consisteix en la reacció d'un precursor en pols ric en aluminosilicats amorfs amb una solució alcalina. L'AAC d'aquest treball, Sust-AAC, és el resultat d'una Tesi Doctoral del Sr. Maldonado-Alameda realitzada en el grup d'investigació DIOPMA (UB). El precursor utilitzat és l'escograva (WBA) i els activadors alcalins emprats són l'hidròxid de sodi i el silicat sòdic.

L'objectiu principal d'aquest present projecte consisteix a avaluar l'impacte ambiental de l'OPC (CEM I) i del Sust-AAC; tot identificant i quantificant els consums d'energia, d'aigua i de matèries primeres, així com les emissions de CO₂. Aquesta avaluació compara les entrades i sortides dels dos ciments en totes les etapes de la seva fabricació; i per tant, permet identificar quin producte presenta un menor impacte en el medi ambient.

Els resultats finals demostren que el Sust-AAC estudiat presenta un impacte inferior al de l'OPC pel que fa a les categories avaluades (consum energia, consum aigua, consum matèries primeres i emissions de CO₂). Tot i això, l'OPC presenta uns resultats més òptims envers l'àmbit estructural. Malgrat això, s'observa que aquests materials alternatius poden ser aptes per aplicacions no estructurals, com per exemple com aïllant tèrmic per tal de millorar l'eficiència energètica dels edificis.

En conclusió, el Sust-AAC es troba en fase de recerca i per aquesta raó no és una alternativa factible avui en dia a causa de la manca d'investigació i conseqüent normalització que garanteixi la seva seguretat i viabilitat com a material de construcció. Tot i això, el Sust-AAC presenta un potencial òptim per poder substituir l'OPC en un futur pròxim permetent assolir els Objectius de Desenvolupament Sostenible (ODS) de l'Organització de les Nacions Unides (ONU).

