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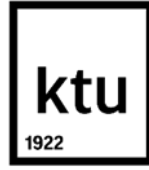
Life-Cycle Assessment of Carbon Dioxide Mineralization Products

Master's Final Degree Project

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Kaunas, 2023



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Environmental Engineering (6211EX003)

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Life-Cycle Assessment of Carbon Dioxide Mineralization Products

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Summary

To study the environmental implications of Portland Cement, magnesia cement, and Portland Slag Cement, this research thesis compares their life-cycle assessments (LCAs), with an emphasis on climate change, human health, ecosystem quality, and resources. By taking into account its possible advantages, including CO₂ capture, a lower calcination temperature, recyclability, and resistance to impurities, the study seeks to determine if magnesia cement is a sustainable alternative to ordinary Portland Cement.

Software SimaPro 9.0 was used to perform a life cycle assessment based on ISO 14040:2007 and 14044:2007 standards. The study was divided into four key phases: determination of the goal and scope, analysis of the inventory, evaluation of the impact, and interpretation. The cradle-to-gate boundary condition was selected to look at the important manufacturing processes of each material. The functional unit of measurement was one tonne of cement.

Scientific literature and the Ecoinvent database were used to gather data about the inputs and outputs of the various cement production processes. Four kinds of damage-oriented impacts were taken into account throughout the impact assessment process using IMPACT 2002+: human health, ecosystem quality, climate change, and resources. A sensitivity analysis was performed which evaluated the validity of the hypothesis and estimated the impact of parameters on the life cycle assessment results.

In comparison to Portland cement and Portland slag cement, magnesia cement has a lower environmental impact across all evaluated impact categories except the human health category, according to the results of the LCA. Notably, magnesia cement production has a 38.6% and 17.8% decrease in climate change impacts compared to Portland cement and Portland slag cement, respectively. In the human health category, magnesia cement has an impact that is about 22% lesser than the impact of Portland cement but about 36% more than Portland slag cement. In the ecosystem quality category, magnesia cement has an impact that is about 87% lesser than Portland cement and about 78% lesser than that of Portland slag cement. In the resources category, magnesia cement's impact is about 95% lower than the impact of Portland cement and about 89% lower than that of Portland slag cement. According to these findings, magnesia cement has the potential to foster sustainability in the cement industry by providing a viable alternative for lowering CO₂ emissions and minimizing its environmental impacts. It is identified that the Abo Akademi process, which entails extracting magnesium from serpentinites and mineralizing CO₂, may be a viable and affordable supply of magnesite. Magnesia cement production offers benefits in the area of climate change since it has a comparatively low carbon footprint.

Onokwai Elizabeth Ogochukwu. Anglies dioksido mineralizacijos produkto gyvavimo ciklo vertinimas. Magistro baigiamojo laipsnio projektas / vadovas Doc. Prof. Inga Stasiulaitė; Kauno technologijos universiteto Cheminės technologijos fakultetas.

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Reikšminiai žodžiai: gyvavimo ciklo vertinimas, anglies dioksido emisija, magnezijos cementas, portlandcementis, portlando šlako cementas, poveikis aplinkai.

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Santrauka

Šiame darbe buvo atliekamas būvio ciklo vertinimas (BCV) skirtingiems cemento tipams, t.y. portlandcemenčiui, magneziniam cementui ir portlando šlako cementui, siekiant įvertinti poveikį aplinkai per skirtingas poveikio aplinkai kategorijas: klimato kaitą, išteklius ir kt. Atsižvelgiant į galimus magnezinio cemento pranašumus, įskaitant CO₂ surinkimą, žemesnę deginimo temperatūrą, perduriamumą ir atsparumą priemaišoms, šiame darbe siekiama nustatyti, ar magnezinis cementas yra tvari alternatyva įprastam portlandcemenčiui.

Darbas atliekamas, naudojant SimaPro 9.0 programinę įrangą, ir remiantis ISO 14040:2007 ir 14044:2007 standartais. Tyrimas buvo suskirstytas į keturis pagrindinius etapus: tikslo ir apimties nustatymas, inventorinė analizė, poveikio aplinkai vertinimas ir interpretavimas. Sistemos ribos visiems trimis produktams buvo pasirinktos „nuo lopšio iki vartų“, siekiant įtraukti ir įvertinti cemento gamybos procesą. Funkcinis matavimo vienetas - viena tona cemento.

Inventoriniai duomenys buvo renkama remiantis moksline literatūra bei ecoinvent duomenų baze. Poveikio aplinkai vertinimui buvo naudojamas IMPACT 2002+ metodas, vertinant šias poveikio aplinkai kategorijas: žmonių sveikatą, ekosistemų kokybę, klimato kaitą ir išteklius. Taip pat atlikta jautrumo analizė.

Remiantis BCV rezultatais, magnezinis cementas, palyginti su portlandcemenčiu ir portlando šlako cementu, turi mažesnę poveikį aplinkai visose poveikio kategorijose, išskyrus žmogaus sveikatą. Pažymėtina, kad magnezinio cemento gamyba sumažina klimato kaitos poveikį 38,6 % ir 17,8 %, palyginti su portlandcemenčiu ir portlando šlako cementu. Žmonių sveikatos kategorijoje magnezinio cemento poveikis yra maždaug 22 % mažesnis nei portlandcemenčio, bet apie 36 % didesnis nei portlando cementui. Ekosistemos poveikio kategorijoje magnezinio cemento poveikis yra maždaug 87 % mažesnis nei portlandcemenčio ir apie 78 % mažesnis nei portlando cemento. Išteklių kategorijoje magnezinio cemento poveikis yra apie 95 % mažesnis nei portlandcemenčio ir apie 89 % mažesnis nei portlandcemenčio.

Remiantis gautais rezultatais, magnezinis cementas yra tvari alternatyva, kuri prisideda prie CO₂ emisijų ir poveikio aplinkai mažinimo. Magnezinio cemento gamyba prisideda prie klimato kaitos mažinimo. Nustatyta, kad Abo Akademi procesas, kurio metu iš serpentinitų išgaunamas magnis ir mineralizuojamas CO₂, gali būti konkurencinga alternatyva kitiems cemento gamybos tipams.

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List of abbreviations

Abbreviations:

PC – Portland cement;

ÅA – Abo Akademi;

PSC – Portland slag cement;

LCA – life-cycle assessment;

GHG – greenhouse gases;

FF – fossil fuels;

BFS – blast furnace slag;

FA – fly ash;

AS – ammonium sulfate;

PFB – pressurized fluidized bed;

ABS – ammonium bisulfate;

BMED – bipolar membrane electro dialysis;

FU – functional unit;

LCI – life-cycle inventory;

LCIA – life-cycle impact assessment;

SA – sensitivity analysis.

Introduction

The issue of climate change presents an imminent danger that necessitates prompt and decisive measures. Global warming is mainly due to rising concentrations of carbon dioxide (CO₂) in the atmosphere. Consequently, sea levels continue to rise, resulting in extreme weather events and glacier melting [1]. Construction industries contribute significantly to greenhouse gas emissions, accounting for more than 7 percent of global CO₂ emissions. [1]. Multiple scholars and experts in the respective domain have proposed diverse strategies to mitigate said emissions. Implementing strategies like CO₂ capture and utilization, choosing energy-efficient production procedures, and accepting alternate cement materials are a few examples of these.

One possible method for lowering carbon dioxide emissions from the cement industry is through mineralization, which involves capturing CO₂ from the atmosphere or industrial flue gases and turning it into stable minerals like carbonates. The strong reactivity and the amount of magnesium minerals in nature make mineral carbonation utilizing magnesium-bearing minerals one of the most promising methods [2].

Background & Significance: Magnesia cement, a form of cement created by the interaction of magnesium oxide (MgO) with water, has recently been the subject of study into its potential as a suitable alternative to Portland Cement (PC). Magnesia cement is said to provide several benefits over ordinary PC. These include the ability to acquire strength by permanently capturing CO₂ and a lower calcination temperature, which makes it more energy efficient. Additionally, magnesia cement has the potential to be completely recyclable at the end of its useful life and not susceptible to impurities. It also absorbs large amounts of CO₂ [3]. Due to the climate crisis, targets have been set for reaching climate neutrality.

The Roadmap for Net Zero Concrete, created by the Global Cement and Concrete Association, intends to achieve net zero concrete by the year 2050. The plan highlights "carbon capture and utilization/storage (CCU/S)" and "savings in cement and binders" as the primary paths for reaching this target, accounting for 9% and 36% of total savings, respectively [1]. Magnesia cement is believed to have the potential to address both areas, but the main challenge is to find a cost-effective way to separate magnesium from magnesium-bearing minerals.

A pilot project to recover magnesium from serpentinites through the Abo Akademi (ÅA) process route is underway in Finland [4]. The project uses technologies called the ÅA process routes to extract magnesium and mineralize CO₂, which can result in long-lasting building materials. While the pilot plant's construction and testing will begin in 2024-2025 [5], the ÅA process generates magnesite (MgCO₃) which is used as a raw material for magnesia cement. . Before reaching conclusions that are definitive, it is essential to conduct a thorough analysis of the environmental effects of cement manufactured by incorporating the aforementioned process in order to determine the potential of magnesia cement in terms of fostering environmental sustainability within the cement sector. In comparison to PC and Portland Slag Cement (PSC), both of which are commonly utilized cement types in the construction sector, there is also less study on the effects of magnesia cement on the environment.

Research Questions & Hypothesis: the thesis aims to answer the following research questions:

- What are the potential environmental impacts and/or benefits when comparing magnesia cement as an alternative to conventional PC and PSC?

- Is Magnesia cement the cement option with the lowest carbon footprint when compared to PC and PSC production?

By addressing the research questions, the thesis seeks to confirm or reject the research hypothesis, which states that the production of magnesia cement and PSC is more environmentally friendly than the production of PC. However, the hypothesis also suggests that the carbon footprint of magnesia cement production is the lowest among the three cement types.

Aim & Objective of Research: This master's thesis aims to perform a comparative life-cycle assessment (LCA) of magnesia cement, PC, and PSC, focusing on their environmental impacts.

The objectives of this study are:

1. To review the available literature on CO₂ mineralization, magnesia cement, as well as previously conducted life cycle assessments on the cement types.
2. To perform inventory analysis of three cement types.
3. To use the LCA methodology to evaluate the environmental impacts of PC, magnesia cement, and PSC, and identify the hotspots in the life cycle of each cement type.
4. To perform sensitivity analysis to aid in assessing the reliability of the results obtained after identifying the hotspots in the life cycle of each cement type.
5. To interpret the results and findings of LCA, and provide recommendations and insights on the potential of magnesia cement as a sustainable alternative to traditional cement types.

The layout of the Report: The organization of this master's thesis is as follows. A review of the literature on CO₂ mineralization, magnesia cement, and the LCA methodology is given in Chapter 1. The methodology employed in this study, including the functional unit, system boundaries, and required data for inventory analysis, is covered in Chapter 2. The results of the LCA and a comparison of all three types of cement are reported in Chapter 3. The chapter also discusses the results' implications and makes recommendations for additional research.

1. Literature Review

1.1. Cement Industry & Sustainability of Cement

Cement is a significant component of concrete and hence plays a vital role in the construction sector. The cement industry has recently faced a number of problems in spite of its importance, notably with regard to environmental issues. Cement is a major contributor to GHG emissions since CO₂ is released during cement manufacturing. In an effort to reduce its carbon footprint and use more sustainable methods of production, the sector has been constantly scrutinized [1].

The cement industry has been investing in innovative technology and production techniques to increase sustainability and lower emissions as a response to these concerns. The investigation of alternative fuels, such as waste products, and the creation of low-carbon types of cement, are examples. Additionally, the sector has been putting energy-saving measures into practice, including deploying more efficient kilns and machines and lowering the clinker content of cement [6].

The cement industry still must find solutions to several issues, including how to make sustainability and carbon reductions more affordable. The industry must also address issues with raw material availability and quality, as well as escalating competition from non-traditional building materials.

To continue developing and growing and to ensure the security of our planet, the construction industry must prioritize sustainability. In addition, natural resources like limestone are running out, which threatens the sector's future. Finding long-term solutions to the difficulties and detrimental environmental effects associated with the production of cement is essential. Constructions made of cement and concrete that are sustainable should produce little waste, have less impact on the environment while being built, and employ recycled materials. Utilizing "green" materials, with inexpensive energy costs, outstanding durability, and minimal maintenance required, may produce high-performance varieties of cement and concrete [1]. The concept of sustainability entails taking into account both short-term and long-term impacts.

1.2. Global CO₂ Emissions from Cement Production

Cement production has been criticized for using a lot of energy and emitting a lot of CO₂ into the air. According to a study from the United Nations Framework Convention on Climate Change (UNFCCC), the cement sector contributes more than 5% of all anthropogenic CO₂ emissions worldwide [6]. The cement industry is also a significant contributor of sulfur dioxide (SO₂), nitrogen oxides (NO_x), and particulate matter (PM) in some nations with weak air pollution control laws. China, India, and the United States produced more than half of the cement used in the globe in 2016 [7]. Global cement consumption is predicted to rise, with the greatest percentage of growth from third-world countries in Africa and Asia [7].

The exact amount of GHG emissions produced by the worldwide cement industry is unclear and this can cause misunderstanding because the information that is currently available is inconsistent [8]. In 2019, a report was published on the energy and CO₂ emission intensity of the cement sector in 14 top cement-producing countries, which account for more than two-thirds of global cement output [9]. The total CO₂ emissions of the global cement sector were calculated using weighted average CO₂ intensities, taking into account changes in clinker-to-cement ratios among different countries. According to the findings, the worldwide cement industry produced approximately 2.3 gigatonnes

(Gt) of CO₂ emissions in 2019, with the majority (60%) coming from the calcination process and the rest (40%) from electricity and fuel use [9]. In comparison to the global GHG emissions of 52 Gt carbon dioxide equivalent (CO₂-e) in 2019 reported by the UN Emissions Gap Report 2020 [10], the cement industry accounted for 4.5% of total global GHG emissions, and 7% of total global CO₂ emissions as reported by the International Energy Agency (IEA) [11].

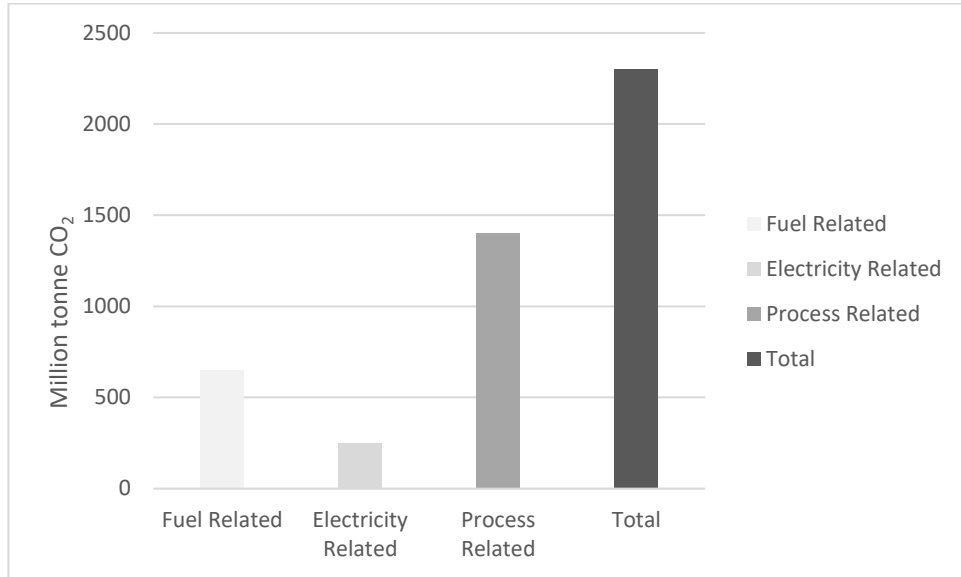


Fig. 1. Global Cement Industry's CO₂ Emissions in 2019 (reproduced from [8])

1.3. Mineralization of CO₂ in the Cement Industry

The global demand for cement is projected to rise by 12% to 23% by 2050 due to the expanding population, urbanization, and infrastructure needs [11]. To meet the goal of carbon neutrality by 2050, reducing CO₂ emissions in the cement sector is crucial. The primary component of cement, calcium silicate hydrate (C-S-H), has the potential for CO₂ mineralization, as confirmed by research conducted by Liu et al [12]. Studies reviewed by Wang et al. indicated that CO₂ mineralization can enhance the mechanical properties of concretes and aggregates that are recycled [13]. Additionally, direct aqueous CO₂ mineralization, carbonation mixing, and curing can play a vital role in reducing CO₂ emissions as reported by Thonemann et al [14]. Direct aqueous CO₂ mineralization products can be employed as additional cement materials or aggregates in concrete. Carbonation curing in a pressurized CO₂ environment results in a C-S-H and calcite hybrid binder structure. Carbonation mixing, which involves introducing CO₂ gas into the cement mixture, forms CaCO₃ nanoparticles and improves the concrete's compressive strength or reduces the amount of binder needed.

1.3.1. CO₂ Mineralization Pathways

In line with the goal of the Paris Agreement, over 197 nations have the objective of reaching carbon neutrality to limit the global temperature rise to less than 1.5°C above pre-industrial levels [15]. To achieve this objective, various measures will be taken such as raising carbon taxes, reducing the reliance on fossil fuels (FF) in energy production, promoting the adoption of renewable energy sources and electric vehicles, and cutting carbon emissions from industries [16]. Among the methods to decrease CO₂ emissions, CO₂ mineralization also referred to as mineral carbonation, is considered to be highly effective [17]. Mineralization of CO₂ is a process in which CO₂ is converted into solid

carbonates through a chemical reaction with naturally occurring minerals as represented by equations (1.3.1.1) and (1.3.1.2).



In the equations “Me” stands for a divalent metal, such as magnesium (Mg^{2+}), calcium (Ca^{2+}), or iron (Fe^{2+}), and the resulting compounds are magnesite ($MgCO_3$), calcite ($CaCO_3$), or siderite ($FeCO_3$), respectively. Materials that are suitable for CO_2 mineralization are readily available worldwide, including various silicate minerals containing divalent metals such as peridotites (ultramafic rocks with less than 45% SiO_2) and basalts (mafic rocks containing 45-52% SiO_2), as well as oxide minerals such as steel slags and fly ashes from industrial waste [16].

While natural CO_2 mineralization processes are possible, they develop relatively slowly. In order to have a bigger influence on mitigating global warming, efforts are being done to accelerate these responses [18]. As shown in Fig. 2, there are several types of CO_2 mineralization, including passive, in-situ, ex-situ direct, and ex-situ indirect carbonation. The dissolving of silicates or oxides, regardless of the technique, is the phase that often reduces the rate of CO_2 mineralization [19].

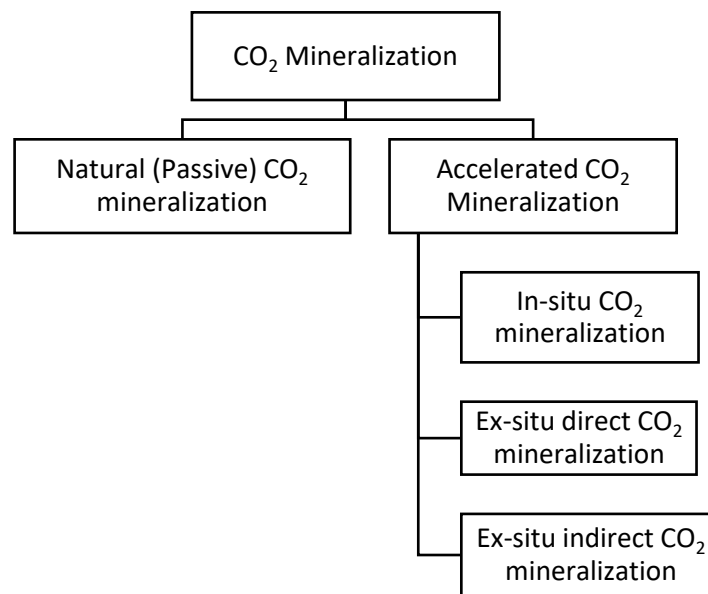


Fig. 2. CO_2 mineralization methods (reproduced from [16])

CO_2 mineralization is an important way for carbon capture, storage, and utilization, but it is limited by certain conditions. It requires a high-pressure CO_2 source, high temperatures above $150^\circ C$, small particle size, and specialized pressure autoclave reactors. As a result, it is not yet economically feasible for commercial use. To make it more cost-effective, it may need to be combined with other techniques to lower capital costs [16].

1.3.2. Natural (Passive) CO_2 Mineralization

Natural or passive CO_2 mineralization is a carbonation process that takes place in typical atmospheric conditions without the need for special reactors. This technique makes use of the weathering processes that occur naturally. Rock that has been exposed to the environment interacts with the CO_2

in the air, slowly turning it into carbonates that safely store the CO₂. According to estimates, the peridotite in the area may be able to carbonate more than a billion tons of CO₂ each year, researchers have discovered evidence of this process in Oman [20]. Natural CO₂ mineralization has cheap initial costs, which is one of its key advantages and may make it a viable option for the mining sector to use waste. Large amounts of mine tailings, which are tiny fragments of rock containing silicate minerals like olivine, serpentine, and pyroxene, are regularly produced by mining operations. Mining firms may use the tailings to passively react with atmospheric CO₂ and generate mineral carbonates for long-term storage since these minerals are ideal for CO₂ mineralization.

According to Power et al., the effectiveness of passive CO₂ mineralization depends greatly on the presence of brucite [Mg(OH)₂] in mine tailings [21]. Brucite can make up 1% to 15% of ultramafic mine tailings [22], and if it all reacts, as shown in equation (1.3.2.3), it can remove a significant amount of CO₂ from the atmosphere. Furthermore, the natural weathering of olivine to serpentine [Mg₃Si₂O₅(OH)₄] can also generate brucite, which can be used for CO₂ mineralization, as demonstrated in equation (1.3.2.4).



Natural CO₂ mineralization may be the best option for carbon capture, pressurization, storage, and transportation due to its low costs. However, mining companies may look to make it more economically viable by utilizing the products created through the process. In the future, natural CO₂ mineralization may be improved by combining it with product utilization and enhancing the natural weathering process. This could lead to benefits such as the recovery of metals [23] and the creation of aggregates for use in the manufacture of cement and materials for construction [24].

1.3.3. In-situ CO₂ Mineralization

The process of in-situ CO₂ mineralization operates similarly to the passive pathway in that CO₂ is injected underground in the form of a gas mixture or fluid to encourage carbonation reactions with minerals without mining [25]. The CarbFix project in Iceland is the most successful example of this method, using pure CO₂ gas or CO₂-H₂S gas mixtures that are dissolved into water and then pumped underground via a drilled well [26]. Basalt rocks, which are prevalent on Earth, are the target for the reaction [27]. To monitor the process, monitoring wells have been drilled, and it was discovered that in two years, nearly 95% of the injected CO₂ was converted into stable mineral carbonates [27]. The basalt rocks break down and release divalent metal ions, typically Ca²⁺, which precipitate as mineral carbonates as the pH rises as a result of the basalt-consuming protons.

The Big Sky Carbon Sequestration Partnership has spread in-situ mineralization throughout the United States as a result of the CarbFix project's success [28]. This method has also been tested on peridotites, another prevalent rock type on Earth [29]. However, because of their low permeability and porosity, in-situ CO₂ mineralization with peridotites has not yet been successful [29]. In-situ mineralization is likely to keep playing an important role in carbon sequestration in the future, depending on the availability of sufficient silicate resources, seismic activity, permeability, and porosity of geological and mineralogical features [30]. Furthermore, in-situ CO₂ mineralization could potentially be used for enhanced oil recovery [31].

1.3.4. Direct Ex-situ CO₂ Mineralization

Both natural and in-situ CO₂ mineralization require several years to achieve the carbonation reaction. As a result, researchers are working to accelerate the process of mitigating global warming. Ex-situ direct CO₂ mineralization, which happens in an aqueous solution because the chemical reaction in water is quicker than a gas-solid interaction, is the most common laboratory-size study in this field [32]. To maximize the rate of ex-situ direct aqueous CO₂ mineralization, specific reaction conditions such as increased temperature and high CO₂ pressure, smaller particle size, and the use of pressurized reactors are required. To accelerate the mineral carbonation process, sodium salts for example sodium bicarbonate and sodium chloride could be added to the solution [33]. Wang et al. [34], obtained a 78% carbonation efficiency in 5 hours using pure olivine for CO₂ mineralization. They discovered that high-pressure CO₂ and sodium salt concentrations were critical for overcoming the difficulties of diffusion via passivation layers.

They also found that serpentine minerals required heat pre-treatment to be reactive for carbonation, which may increase the capital cost [35]. According to Wood et al., they discovered that the Fe(II) content in olivine has an impact on CO₂ mineralization [36]. The Fe(II) in olivine can turn into hematite (Fe₂O₃) during the process of carbonation, and this reaction can hinder CO₂ mineralization. Therefore, the more Fe(II) that is present in olivine, the harder it becomes for CO₂ to mineralize. They recommended that a reductive gas, 1% H₂, can be added to accelerate the process. Direct aqueous CO₂ mineralization is also possible with steel-making slags, coal fly and bottom ashes, and smelter waste, however, capital costs have not been greatly reduced. Therefore, future research in direct aqueous CO₂ mineralization may focus on how products are utilized or how the technology is integrated with other technologies.

1.3.5. Indirect Ex-situ CO₂ Mineralization

To address the fact that the dissolution of silicates and oxides containing divalent metals is often the slowest step in CO₂ mineralization, ex-situ indirect CO₂ mineralization has been created as an alternative. The silicates or oxides are dissolved to liberate divalent metals, which then precipitate as mineral carbonates under various conditions. The temperature swing process [37] and the pH swing process [38] are the two most frequent procedures for ex-situ indirect CO₂ mineralization. Zevenhoven et al. [37], created the Abo Akademi (AA) route, which utilizes the temperature swing process. The process involves dissolving the silicate mineral as magnesium sulfate at around 400°C using ammonium sulfate, then extracting the magnesium as magnesium hydroxide at less than 100°C, followed by CO₂ mineralization at approximately 450°C. The advantages of the AA route include utilizing the heat generated from the CO₂ mineralization reaction and being able to recycle the ammonium sulfate reagent. The AA route would be further discussed in subsequent sections of this work.

The other common process for ex-situ indirect CO₂ mineralization is based on the Ph-swing route [39]. This entails releasing divalent metal ions from the silicate or oxide minerals into the aqueous solution by dissolving them in acid with a low pH value, and then adding an alkali to raise the pH, causing the metal ions to precipitate as mineral carbonates. While the pH-swing process has been proven effective, one of its challenges is the difficulty of recycling the acid and alkali reagents, which contributes to higher overall costs for the process. The efficiency of pH-swing CO₂ mineralization, according to Hosseini et al., primarily depends on the reagents' capacity to be recycled, with

ammonium chloride being a viable option [40]. Indirect CO₂ mineralization may be studied on a range of slags and waste materials in addition to natural silicates and oxides. [41]. Looking forward, ex-situ indirect CO₂ mineralization is expected to play a significant role in CO₂ mineralization and offer high carbonation efficiency. However, reducing the cost of reagents is still a challenge, and ways to make the entire process more economical are being explored, including the utilization of byproducts and the integration with other technologies. Like direct CO₂ mineralization, the development of ex-situ indirect CO₂ mineralization is an ongoing process with promising prospects.

1.4. Ordinary Portland Cement

PC is the world's most frequently used material for construction, having been invented in the early nineteenth century in Britain and named after a stone on the British coast [9]. PC was originally made by heating limestone and clay, which hardened when combined with water. This type of cement is known as hydraulic cement [42]. Cement is now manufactured by quarrying, crushing, or grinding raw materials such as limestone and clay, which are then blended and processed through a kiln as a dry powder or a wet slurry. The production of cement is frequently centered around geological resources and cannot be readily relocated. The kiln temperature can reach above 1,500°C, fusing the raw ingredients into clinker pellets, which are subsequently cooled, mixed with gypsum, and pulverized to produce the fine powder known as PC [9]. More detailed information about the process of cement production, including the energy and CO₂ emissions impacts, is provided in the subsections below.

1.4.1. Process of Cement Production

1.4.1.1. Mining & Quarrying

Limestone is the primary raw material required to create cement, and it is often sourced from a quarry near the cement factory. The quarry provides the necessary calcium oxide, while clay, shale, and other minerals provide the silicon, aluminum, and iron oxides required for cement production. Mining and transporting raw materials from the quarry account for around five percent of the total CO₂ released produced during cement production [43].

1.4.1.2. Raw Material Grinding and Preparation

Whether dry or wet processing is employed for the formation of clinker affects the choice of the grinding technique. The initial components are processed into powdered form in dry processing using ball grinders, roll presses, or vertical roll grinders. Dry feed is typically dried to a moisture level of 0.5% using auxiliary or waste heat. However, if the initial materials are moist, wet processing, in which the beginning materials are processed in a ball or tube mill with water to produce a slurry with between 35 and 40% moisture might be preferable [44]. Electricity used for grinding cement raw materials is high; it typically ranges from between twenty-five and thirty-five kilowatt-hours (kWh)/tonne of raw material [9].

1.4.1.3. Production of Clinker

The production of clinker is a crucial step in cement production that requires high-temperature heating and consumes the most energy. Kiln systems are used to evaporate raw meal water, calcine carbonate components, and generate cement minerals. The dry rotary kiln is the most often used form of the kiln, which directly heats and calcines the raw meal. Pre-calciner technology was recently developed

to increase manufacturing efficiency, and preheaters were introduced for warming the raw meal in advance of its entering the kiln. Clinker is quickly cooled using a tube/planetary cooler or grate cooler in older facilities. The clinker is moved across a revolving grate by the grate cooler's perpendicular air flow [44]. 2.9 to 3.8 GJ/t clinker is the typical fuel consumption for a dry kiln with at least four preheating steps [9]. More than 90% of the energy required in the cement industry, almost all fuel used, and the great bulk of CO₂ emissions associated with the cement manufacturing process are attributed to the production of clinker [11].

1.4.1.4. Grinding to a finish

To create powdered cement, the clinker nodules are further ground in ball mills, roller presses, or roller mills, and just a little quantity of gypsum is added to control setting qualities. Nowadays, factories use high-pressure vertical or horizontal roller mills to conserve electricity. Before testing and bulk distribution via various modes of transportation, the finished cement is held in silos [44]. The amount of additives, target cement fineness, and material hardness all affect how much electricity is consumed during final grinding. Fig 3 depicts the specific phases of producing cement with a rotary kiln [45], while Fig. 4 displays typical energy usage by process steps in a dry rotary kiln cement plant [46]. Electricity is used for motor-driven systems including grinding, conveyors, and kiln drives, while fuel is burnt in the kiln to make clinker and occasionally for raw material drying.

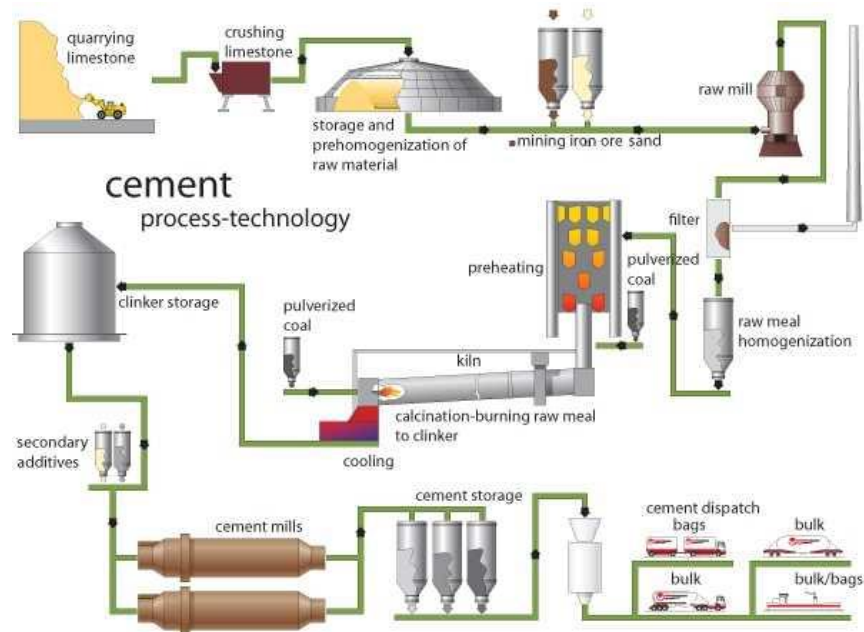


Fig. 3. Steps involved in Cement Production Process with Rotary Kiln (reproduced from [45])

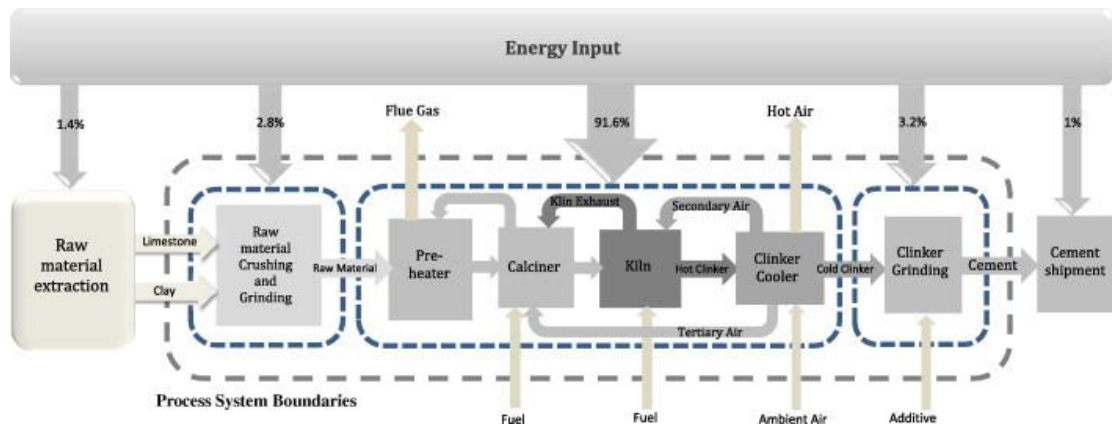


Fig. 4. Energy Consumption Breakdown in a Conventional Cement Plant with a Rotary Klin by Process Phase (reproduced from [46])

1.5. Types of Blended Cement

Blended cement is made by mixing PC clinker, which is heated to temperatures of around 1400-1500°C, with supplementary cementitious materials (SCMs) like fly ash or BFS. The production process involves combining one or more additives, with the most commonly used materials being BFS, fly ash, and silica fume [47]. Blended cement has various advantages for both consumers and producers, including reducing fly ash inventories at ready-mix locations, providing consistent product quality, and offering early strength and workability [47]. The ASTM Standard Specification for Blended Hydraulic Cement (ASTM C595) specifies the appropriate amount of granulated blast-furnace slag or natural or manufactured pozzolans that should be used to make blended cement [48]. The advantages of blended cement are divided into two categories: environmental and performance-related. Blended cement may make concrete more cost-effective, boost strength and durability, and change other qualities by employing supplemental cementing materials. Four types of blended cement are identified by ASTM [48], which are discussed below.

Type IS (X), or PSC, is made by blending PC clinker and granulated BFS, with a required amount of gypsum. Iron production in blast furnaces generates slag as a by-product, which is a mixture of non-metallic minerals left over after the iron is extracted. Depending on the cooling method, slag can become waste, construction aggregate, lightweight aggregate, or hydraulic cement. Rapid cooling of slag with water results in granulated slag, which has a sand-like consistency and can be ground into a fine powder to produce slag cement. The application of slag cement in concrete is widely known and offers various advantages, such as reducing the need for virgin materials, lowering GHG emissions, and reducing energy consumption. Slag cement can be substituted for PC in concrete mixtures, with substitution rates ranging from 25 to 80 percent depending on the application. By replacing PC in everyday concrete, slag cement can significantly decrease the embodied GHG emissions and energy consumption of this widely used building material [47]. For the comparative LCA of this study, PSC is the blended cement type selected to be compared with magnesia and PC.

Type IP (X), or Portland-Pozzolan Cement, is produced by either inter-grinding ordinary PC clinker, gypsum, and pozzolanic materials or grinding them independently and fully mixing them. The most prevalent pozzolan in blended cement is fly ash. High compressive strength Portland-Pozzolan Cement prevents concrete from reacting with alkali and makes it more solid and impermeable [47].

Type IL (X), or Portland-Limestone Cement, is a blended cement with a greater limestone component that decreases the carbon footprint by 10%. It has qualities identical to ordinary PC and may be manufactured at any PC manufacturing plant. It has better durability, placement and finishing qualities, shrinkage and heat of hydration, and setting and strength performance [47]

Ternary Blended Cement, or Type IT, is created by combining PC (clinker + gypsum) with two complementary cementitious materials such as fly ash, slag, silica fume, or pozzolans. It possesses excellent strength, corrosion resistance, area-specific resistance, thermal cracking resistance, low permeability, and sulfate resistance. It is referred to as ternary since it is composed of three parts [47].

1.6. Reactive Magnesia Cement

There are currently three efforts addressing challenges with ordinary PC: reducing energy consumption by using low-energy production techniques, renewable energy sources, and alternative raw materials; replacing some cement with low-carbon materials, waste, and industrial byproducts; and developing new cement formulations with potential lower carbon footprints [49]. One promising option is reactive magnesium oxide (MgO) cement, which some researchers believe may be manufactured with lower CO₂ emissions and even a positive CO₂ balance by absorbing the surrounding carbon dioxide and converting it into magnesium minerals [50]. In certain calcination and reactivity conditions, MgO offers additional advantages that include lowering thermal shrinkage, lowering the cost of cooling concrete, and accelerating construction by enabling continuous casting devoid of requiring as many cold joints [51]. Yet, environmental concerns are the main driving force behind the development and expansion of MgO-based cement, since their lower production temperatures and capacity to absorb CO₂ make them desirable for "carbon neutral" cement production [52]. As a result, there has been a recent increase in academic and commercial interest in MgO-based cement.

1.6.1. History and Development of Reactive Magnesia in the Cement Industry

MgO is used in various construction applications such as fire-resistant wood chips and magnesium sulfate cement light insulation panels [53], and expansion additives based on MgO to correct the shrinkage of concrete in dams [54], fire protection and rapid repair using magnesium phosphate cement [55]. In addition, research is underway on the development of reactive magnesia cement as a binding agent that increases strength through carbonation. The research combines MgO from magnesium silicates with magnesium carbonate in the hydrated form to develop a new cement system that is believed to be low in carbon [56]. Fig. 5 depicts a timeline of MgO consumption in cement as reported by several commercial and research institutes [53].

The modified magnesium cement formulations developed and patented by Australian scientist John Harrison ten years ago [57], have some sustainability advantages over traditional PC and have received a lot of publicity in *New Scientist* [58] and the *Guardian* [59]. These blends of PC and reactive MgO, sometimes including fly ash, are designed for a variety of applications, from structural concrete to porous masonry units. three different types of cement compositions, each with unique advantages. These three types of cement are tec-cements, enviro-cements, and eco-cements [3]. Tec-cements have a lower concentration of magnesium oxide (MgO) compared to PC. This lower concentration of MgO results in increased durability and strength in concrete applications due to increased density, decreased permeability, internal dryness, and long-term pH and volume stability. Enviro-cements have the same concentration of MgO as PC, and they are useful for waste

immobilization because of brucite's lower solubility and mobility. Additionally, the layered structure and lower stable long-term pH of brucite help to immobilize waste. Finally, eco-cements have a higher concentration of MgO than PC, which makes them useful for porous block applications because they can absorb CO₂ and subsequently carbonate to provide hydrated magnesium carbonates of varying strengths. It is vital to understand that depending on the processing, MgO might have various characteristics. For instance, reactive MgO and PC hydrate at similar rates, but dead-burned MgO hydrates more slowly and has less reactivity due to being calcined at a higher temperature. The process also causes dead burned MgO to crack. The situation is comparable to how PC's characteristics might be impacted by MgO impurities during the clinkering step. When studying the impacts of MgO types on cementitious materials, it is important to take into account the differences between them.

John Harrison, the inventor, has made substantial contributions to the knowledge of the chemistry, interactions, and functioning of PC-MgO systems. Furthermore, research conducted at the University of Cambridge over the last nine years has explored a broad range of reactive MgO systems. These investigations have included the examination of blends with other compounds and aggregates. Additionally, the characterization and fundamental properties of these systems have been studied along with their performance in various applications such as concrete, waste immobilization, and carbon capture and storage [3].

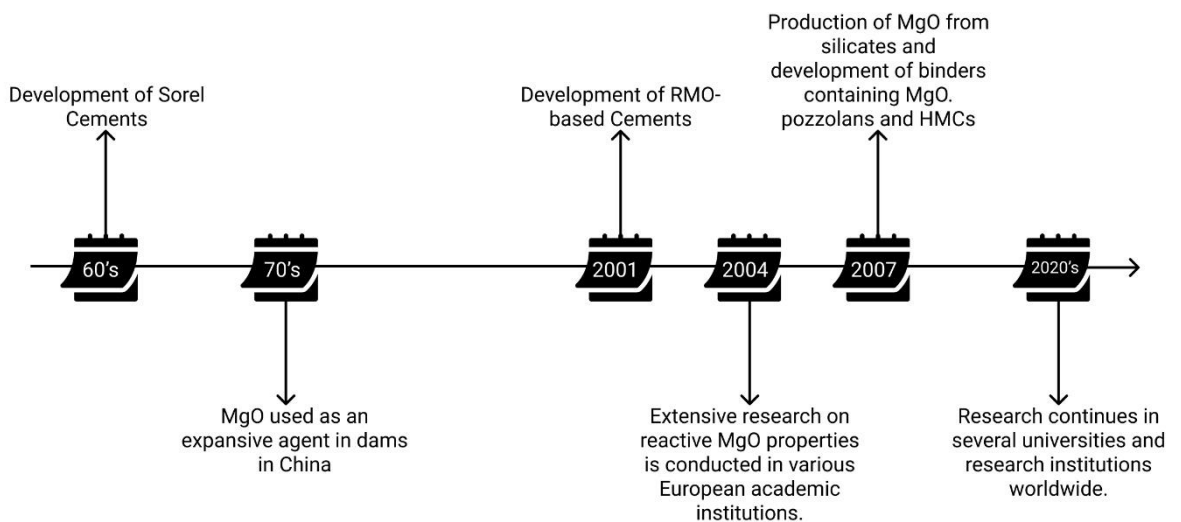


Fig. 5. Timeline of MgO use in the cement industry (reproduced from [53])

1.7. Magnesia Production

Magnesium is a fairly common element found in the Earth's crust and seawater. It is present in several types of rocks and minerals, including dolomite, magnesite, and silicate. The global production of magnesia cement is much smaller compared to PC, with a production of 14 million tonnes annually [60]. Magnesia cement is mainly produced by heating magnesite (MgCO₃), a process similar to producing lime from limestone [52]. Magnesite comes in two varieties: macrocrystalline and

cryptocrystalline. In addition to 47.6% MgO and 52.4% CO₂, it also has evidence of siderite and calcite [49]. Magnesite has several applications, including ceramics, surface coatings, and flame retardants, and it may coexist with dolomite in sedimentary rocks [49]. Magnesite has vast resources, but just a few countries—China, Russia, India, North Korea, Australia, Turkey, and Slovakia—control 75% of its global production [49]. China stands out as the worldwide leader among them with 3.7 billion tonnes of magnesite deposits, or around 29% of the world's total reserves [61]. China also produces, consumes, and supplies the most magnesium oxide, which is derived from magnesite.

Magnesite is used to make around 8.5 million tonnes of MgO per year [62], with China, Russia, and Turkey generating 49%, 12%, and 6% of the total respectively [63]. Fig. 6 depicts a graphic depiction of the world's magnesite sources and the nations where the majority of MgO is produced [53]. Calcination, or heating magnesite to make MgO, is typically done in shaft or tunnel kilns. However, China's weak quality control measures lead to unexpected calcination process parameters, including temperature and residence duration. This might result in large temperature changes throughout the kiln and MgO with different levels of reactivity.

The primary components of magnesium, chlorides, and sulfates are found in saltwater and brine, which are utilized to create a small amount of MgO. A strong base is added to help in the precipitation of magnesium hydroxide (Mg(OH)₂), which is subsequently thermally decomposed [3].

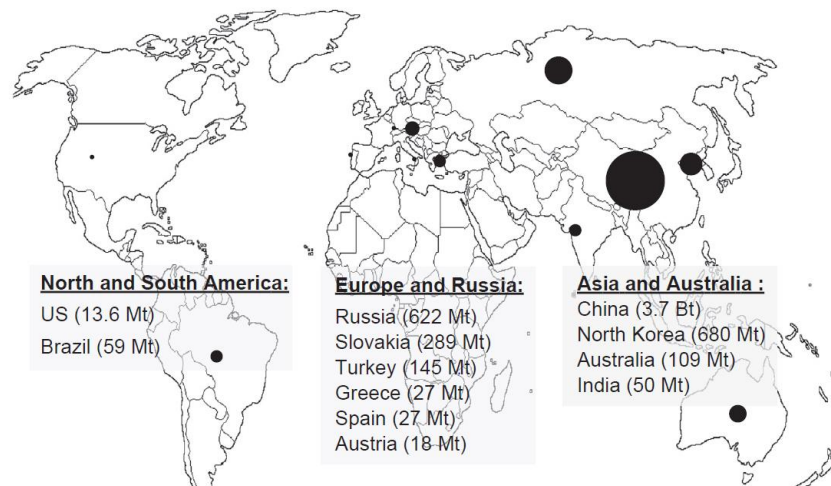


Fig. 6. Distribution of magnesite reserves globally and major countries producing MgO (reproduced from [53])

1.7.1. Magnesite Calcination

The main method for producing MgO, as stated in equation (1.7.1.5), is magnesite calcination due to the wet process' high energy requirements. However, this method generates 1.08 tonnes of CO₂ for every tonne of pure magnesite that is converted into MgO. CO₂ pressure and temperature have an impact on MgO synthesis. Depending on the required MgO reactivity, a different temperature is utilized in the kiln to calcine magnesite. Four commonly synthesized types of magnesium oxide are shown in Table 1 [64]. These include light-burned MgO, which is calcined at 700–1000 °C and has the highest reactivity and specific surface area among MgO forms. In contrast to light-burned MgO, hard-burned MgO is calcined at temperatures between 1000 and 1500 °C and has a reduced reactivity and specific surface area. The distinct form of MgO that is calcined at temperatures between 1400

and 2000 °C, known as periclase, has the lowest specific surface area and almost no reactivity. Fused MgO is the least reactive kind of MgO and is calcined at 2800°C.



Table 1. Types & Properties of MgO [64]

MgO type (Grade)	Temperature of Calcination (C)	Reactivity	Crystallinity	Specific Surface Area
Light-burned (reactive, caustic-calcined)	700 – 1000	Biggest	Smallest	Biggest
Hard-burned	1000 - 1400	Smaller	Bigger	Smaller
Dead-burned (periclase)	1400 - 2000	Much smaller	Much bigger	Much smaller
Fused	>2800	Smallest	Biggest	Smallest

1.7.2. Magnesium hydroxide Calcination

As indicated in equation (1.7.2.6), calcining magnesium hydroxide entails heating a filter cake that contains 50-72% magnesium hydroxide solids. The process used to create magnesium oxide (MgO) from brine or seawater is comparable to this one. Usually, the process begins around 350°C and quickly rises in temperature. Several processes, including dehydration of the filter cake, breakdown of the dry magnesium hydroxide, and MgO sintering, take place throughout this calcination process. However, it might be difficult to remove chemically bound water from magnesium hydroxide without exceeding 1000°C in temperature [52].



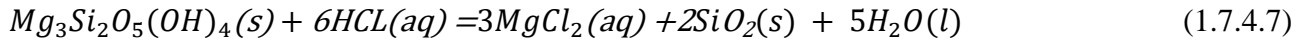
1.7.3. Seawater and brine

Through the alkaline precipitation of brucite (Mg(OH)₂) from saltwater or magnesium-rich brine, magnesium oxide (MgO) can be produced. To remove carbonates and reduce the pH of the saltwater to about 4, pre-treating it with sulfuric acid is necessary. The pH is then increased above the level at which brucite begins to precipitate (pH 10.5) by adding an alkali. As a result, brucite is created, which may later be calcined to yield MgO [52]. Another MgO production method is carbonation [65], which produces different types of magnesium carbonate depending on temperature and CO₂ pressure using natural or waste solutions. After obtaining magnesium carbonate, it is calcined to produce MgO. However, this process requires higher energy than magnesite calcination. The wet process route used to produce MgO from MgCl₂-rich brine or seawater is considerably more complicated than the calcination of MgCO₃. Although this production method has higher energy requirements and costs, the final product's purity (> 97%) justifies its use in specific pharmaceutical or food industry applications [66].

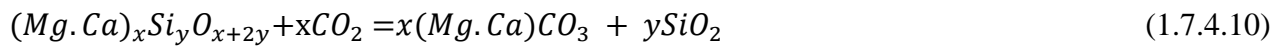
1.7.4. Magnesia extraction from Magnesium bearing minerals

This approach relies on geological CO₂ sequestration, which entails decomposing rocks with carbonation-capable chemical groups into appropriate precursors that can react with CO₂ [52]. The

breakdown of magnesium silicates can be aided by two methods: Mg silicate acid digestion followed by brucite precipitation and calcination. The reaction equations are shown below:



Mg silicate carbonation and Mg carbonate calcination make up the second procedure. The CO₂ pressure and temperature control the kind of Mg carbonate produced by this process. They are calcined after obtaining carbonates to create MgO, CO₂, and potentially H₂O. Magnesite can be synthesized at temperatures of 155°C and pressures of 126 bar, although hydrated magnesium carbonates can be synthesized at lower temperatures and pressures [52].



1.8. MgO Characterization & Properties

Magnesium oxide (MgO) is a widely used material in various applications, including construction, agriculture, and environmental protection. It is commonly used as a cement additive, and its high alkalinity makes it useful in neutralizing acidic soils and flue gases. The reactivity and purity of MgO are critical factors that affect its performance in these applications. As a result, substantial research on commercially available MgOs has been done to better understand their features and characteristics [67].

Researchers have investigated over 20 commercially available MgOs from various sources and manufacturing processes worldwide. The MgOs were produced by different methods, including calcination of magnesite and synthesis using seawater and chemical precipitation. The MgO content varied between 60% and 99.6%, with synthetically produced MgOs having higher purity than those produced by calcination. Most of the impurities in calcined MgOs were the typical rock minerals CaO and SiO₂. On the other hand, synthetic MgOs contained impurities such as CaO, Cl, and SO₃ [3].

MgOs' reactivity is a key feature that defines its use as a cement additive. The researchers found that the majority of MgOs produced for commercial use were probably calcined at temperatures close to the upper limit of the reactive MgO range, or roughly 1000 °C. Their reactive nature will therefore probably be similar to that of hard-burned MgOs. The reactivity of MgOs was measured using the citric acid test, which revealed that it varied significantly, with some MgOs being highly reactive and others highly unreactive. The surface area of MgOs measured was between 2 and 148 m²/g, and the average particle size was between 1.8 and 35 μm [3].

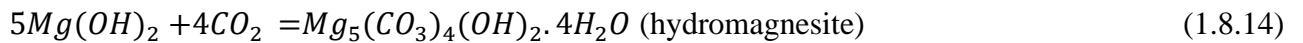
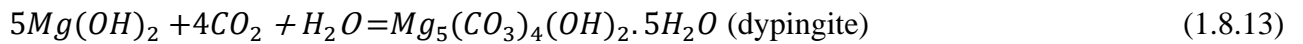
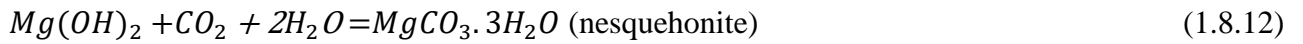
Hydration of MgO is another critical property that affects its performance in applications. MgO combines with water to create magnesium hydroxide (Mg(OH)₂) or brucite during the hydration process. The researchers discovered a hydration level of 40-80%, with a maximum of 80-95%. They also discovered that the addition of specific hydration agents, such as those used with PC (PC), increased the degree and rate of hydration. The CaO concentration was primarily responsible for the substantial fluctuations in the equilibrium pH of MgOs, which varied from 10.0 to 12.5 [67].

Highly reactive MgO may be produced under very controlled calcination conditions, as was revealed during commercial trial production of MgO from magnesite in China. Compared to other MgO products currently on the market in China, this one is significantly more reactive. This finding has significant implications for the production of high-quality MgOs for use as a cement additive and in other applications [68].

To comprehend how reactive MgO behaves in terms of hydration, microstructure, and carbonation, basic investigations of the material have been done both individually and in blends utilizing pastes and mortars [69]. According to equation (1.8.11), the researchers discovered that MgO hydrates to produce Mg(OH)₂ or brucite in the presence of water and at ambient CO₂ levels. At 0.009 g/L at 18°C, brucite has a very poor solubility in water, which limits its use as a cement for binding. Layered in structure, the morphology of brucite varies according to the magnesium source and formation conditions [67].



According to the findings of the researchers, brucite can carbonate to generate either one or more hydrated magnesium carbonates in the presence of adequate CO₂ and water during curing. Depending on the particular formation circumstances, the resultant hydrated magnesium carbonates take the form of dense, well-structured crystal networks with a variety of morphologies. These hydrated magnesium carbonates have a strong capacity to bind, and they are metastable compounds that can change over time into less hydrated forms [3]. The reaction equations are shown below:



1.9. The Åbo Akademi (AA) Process routes

The use of serpentinite, a magnesium silicate, is being explored as a resource for large-scale carbon capture and storage (CCS) via CO₂ mineral sequestration. Numerous methods for serpentinite carbonation have been developed in Finland, where CCS is the sole option for decreasing carbon emissions, as a result of considerable research and development over the past 20 years. These methods involve extracting magnesium using a flux salt and then carbonating a magnesium salt to recover the flux salt. The process routes work directly on a CO₂-containing gas stream without a pre-separation step for CO₂ capture [70]. This section describes the progress of the development of Åbo Akademi (AA) process routes towards serpentinite carbonation.

ÅA route 1: Early work on the activation of the magnesium in serpentinite rocks commenced in 2000, with researchers investigating methods such as heating and grinding to make the magnesium more reactive. However, in 2007, the focus shifted to extracting the magnesium from the rock, with the researchers opting to produce magnesium hydroxide (Mg(OH)₂), which was found to be more reactive with CO₂ than MgO. The researchers discovered that MgCO₃, also known as magnesite, decomposes into MgO and CO₂ at approximately 400°C, with higher temperatures increasing the chemical reaction kinetics for carbonation of Mg(OH)₂ [71] [72]. As such, the research work adopted two parallel tracks which formed the first ÅA process route: production of Mg(OH)₂ powder from serpentinite rock and carbonation of Mg(OH)₂ in a pressurized reactor to produce magnesite powder.

The extraction process involves using ammonium sulfate (AS) in a furnace, typically a rotary kiln, with powdered serpentinite at 400 – 450°C for 30 minutes, producing magnesium sulfate (MgSO₄). MgSO₄ is water-soluble, and solid residues are removed from the aqueous solution to produce a solution containing MgSO₄ and dissolved sulfates of iron and other minor species in the rock. The researchers increased the pH of the solution to 8.5 using NH₃ vapors from the furnace to precipitate several substances, including calcium and chromium salts as well as iron oxyhydroxide. After removing these precipitates, the pH is further raised to 10.5 - 11.0 to precipitate Mg(OH)₂ using the remainder of the NH₃ vapor. The NH₃ is mixed with water vapor released from the furnace, deriving from the crystal water in the serpentine mineral, and no sulfur-containing species were found in these vapors.

In the carbonation step, Mg(OH)₂ is filtered from the aqueous solution of AS and carbonated in a pressurized fluidized bed (PFB) reactor for 10-15 minutes at approximately 500°C, at a CO₂ partial pressure of 20 bar, producing pressurized steam as a byproduct. To obtain purer Mg(OH)₂ with a higher specific surface area for faster carbonation, iron species, and other minor contaminants are removed at a pH of approximately 8.5. Conversion levels consistently reached in the laboratory are approximately 80% for the magnesium extraction step and 70-80% for the carbonation reaction step. Unreacted rock and MgCO₃ can be separated from MgO and Mg(OH)₂ using cyclones, and the unreacted rock has a higher density than produced silica, making it easy to separate from the aqueous solution.

The heat produced at approximately 500°C during the carbonation in the PFB, as well as the hot product solids and gas from the PFB, can be used to preheat the material that enters the furnace for extraction of magnesium from serpentinite, preheat the CO₂-containing gas entering the PFB, and/or the Mg(OH)₂ entering the PFB. Approximately 30-35% of the heat requirements can be covered by the heat from the carbonation reactor, with the remaining heat requirements primarily for the furnace for magnesium extraction [70].

ÅA route 2: The carbonation of Mg(OH)₂ in a PFB reactor may not be attractive due to concerns about waste heat and other factors. Instead, a carbonation process in an aqueous solution can be used, which requires low-temperature heat to reach the optimal temperature of aqueous streams, and avoids the need for electricity consumption to pressurize the PFB. This process called the ÅA2 route involves extracting magnesium and producing aqueous MgSO₄, which is then reacted with CO₂ from flue gas to produce magnesium carbonate hydrate (MCH) MgCO₃·3H₂O, or nesquehonite. This method achieves a higher conversion rate of around 90% of magnesium into nesquehonite, with unreacted MgSO₄ recycled inside the process. The ÅA1 route may be preferable for a lime kiln, while the ÅA2 route would be preferable for a natural gas-fired power plant (NGPP) based on heat and power consumption [73]. The necessary heat for magnesium extraction could be assumed to be available via process integration. A summary of the results obtained at ÅA with the ÅA1 and ÅA2 routes up to 2017 has been published [4], including the use of membrane separation methods and life cycle assessment (LCA) [74].

ÅA route 3: After developing the ÅA1 and ÅA2 routes, efforts were made to recover AS salt through membrane separations and membrane electrodialysis, as explained in Koivisto's thesis [75]. The aqueous solution, which includes Mg, Fe, and contaminants, contains ammonium bisulfate (ABS) resulting from the kiln's excess AS decomposition, making the solution acidic. Raising the pH of the solution converts ABS into AS, which can be removed and returned to the furnace for Mg extraction

using a monovalent anion-selective membrane. Separating ABS requires about 0.2 kWh of electricity per kg ABS [76]. After carbonation, the aqueous solution contains primarily AS in an alkaline solution. Using bipolar membrane electrodialysis (BMED), this solution can be processed into three streams: a more concentrated AS solution, water, and an NH_4OH solution. Before carbonation, the pH of the MgSO_4 solution can be increased using the NH_4OH solution. Separating NH_4OH using BMED requires around 0.9 kWh of electricity per kg NH_4OH separated. Using BMED for an aqueous AS solution produces sulphuric acid H_2SO_4 and an NH_4OH solution. One mole of H_2SO_4 added to one mole AS produces two moles of ABS, which is used for Mg extraction, and an NH_4OH solution that raises the pH of the MgSO_4 solution. This process requires around 0.4 kWh of electricity per kg AS processed. However, the given electricity consumption numbers should be used with caution as they depend on concentrations used in the experimental work versus a large-scale process. As a result, a third, ÅA3 route was designed that includes optional reverse osmosis membrane (pre-) separation for removing water from the process flows.

ÅA route 4: The researchers investigated the extraction of magnesium from serpentinite using a mixture of ABS and AS in an aqueous solution at ambient temperatures. Tests in 2008 [77] showed that a 1:1 molar ratio of ABS and AS extracted good levels of magnesium, which is similar to using aqueous ABS only [78]. This method avoids the high energy requirement for full thermal decomposition of AS into ABS and NH_3 . BMED can produce sulphuric acid to make ABS by mixing it with AS. A fourth route, ÅA4, was suggested that relies on BMED to produce sulphuric acid and NH_4OH solution to raise the pH for the MgSO_4 solution's carbonation, offering a solution to locations where waste heat is not available. Heat pump technology can produce heat up to 80-90°C, which is beneficial for Mg extraction [78], and renewable electricity is becoming increasingly available for large-scale heat output.

ÅA route 5: The need for a high CO_2 pressure of 20 bar in a PFB reactor is a significant drawback for carbonation, as it requires compression to levels above 100 bar, especially for diluted flue gases. Additionally, the PFB carbonation reactor may not produce enough heat for extracting Mg from serpentinite at 400-450°C. However, if high CO_2 concentrations in the gas motivate the use of a PFB carbonation reactor and no other heat source is available, then the most energy-efficient route ÅA1 can be used. This is often the case in bioenergy and bio-refinery process sites. If electricity is available and economically attractive, and no waste heat is present, then membrane-based technologies and considerations can be combined with the use of a PFB carbonator. This gives the most recent and fifth route, the ÅA5 process, as shown in Fig. 7. The use of a PFB carbonator provides some heat from the compression intercooler and the PFB reactor [70].

In subsequent sections of this work, the ÅA route 5 is identified as the Abo Akademi route. Considering its recentness, the acquisition of magnesite for the production of magnesia cement, as assumed in the LCA, relies on the AA route 5.

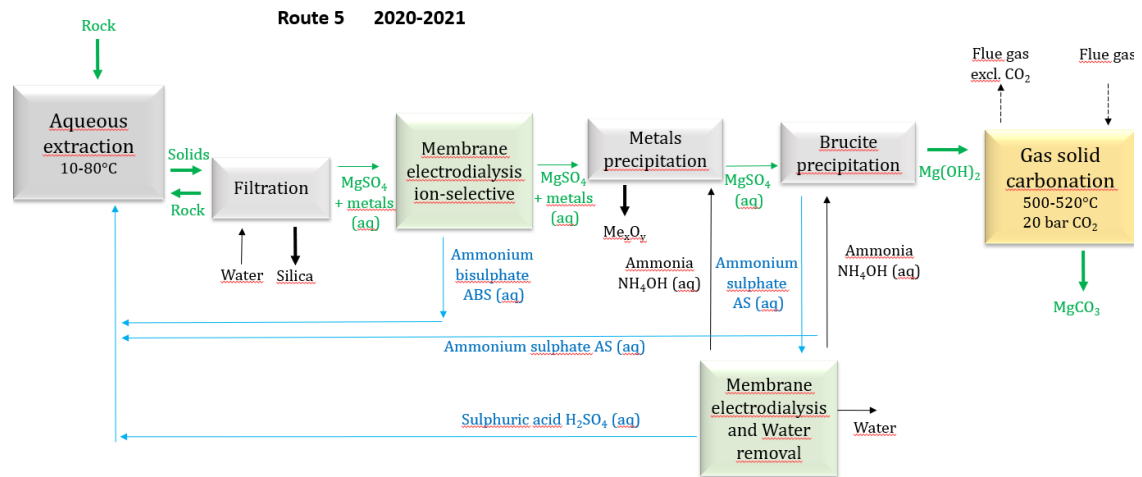


Fig. 7. ÅA process route 5, based on wet extraction of magnesium and dry carbonation, improved with membrane separation methods (reproduced from [70])

1.9.1. The main difference in Åbo Akademi (ÅA) routes

The first method involves extracting Mg at high temperatures, removing any leftover materials and impurities, and then producing $Mg(OH)_2$ and carbonate in the gas phase. The second and third methods are similar to the first but involve carbonation in water and using NH_3 to raise the pH. The fourth and fifth methods involve aqueous extraction, membrane separation, and precipitation of metals. In the fourth method, NH_3 is used to raise the pH and produce $NH_3(aq) + H_2SO_4(aq)$ from ammonium sulfate (aq) after filtration of nesquehonite. In the fifth approach, reverse osmosis or mechanical vapor recompression can be employed to remove part of the water from the solution while still producing $Mg(OH)_2$ and carbonate in the gas phase. The following list provides a brief summary of each process's steps:

ÅA route 1: hot solid/solid Mg extraction + hot gas/solid carbonation

ÅA route 2: hot solid/solid Mg extraction + aqueous carbonation

ÅA route 3: hot solid/solid Mg extraction + membranes for ions separation and acid + base production from salt + aqueous carbonation

ÅA route 4: aqueous Mg extraction + membranes for ions separation and acid + base production from salt + aqueous carbonation

ÅA route 5: aqueous Mg extraction + membranes for ions separation and acid + base production from salt + hot gas/solid carbonation.

1.10. Life Cycle Assessment Research in Cement Industry

LCA is a methodical approach to evaluating the environmental impact of products. It involves analyzing the environmental impact of processes, from obtaining raw materials to disposing of waste [79]. LCA allows for the assessment of various effects, such as climate change and resource depletion, by measuring energy and materials consumption and waste emission [79]. By doing so, LCA reduces the negative environmental impact associated with a product or process, allowing manufacturers to use the Best Available Techniques (BAT) [66]. While there have been numerous LCA studies

conducted on clinker production, the same cannot be said for alternative cement. This section reviews prior LCA studies on the manufacturing and use of alternative cement as well as prior studies on the energy use and environmental impacts of producing magnesium and magnesium alloys.

The goal of the study carried out by Tanzer et al [80] was to investigate potential strategies for lowering carbon emissions in the cement sector. Utilizing biomass for energy is one such strategy that can considerably cut carbon emissions. The research also considered the natural carbonation of demolition concrete at the end of its lifespan and mineral carbonation during concrete production as viable methods to reduce carbon footprints. The study found that if emissions from manufacturing are reabsorbed through biomass regeneration and CO₂ absorption by concrete waste, concrete production may have a smaller carbon footprint and might become CO₂ negative after 40 years. Additionally, the carbon footprint of mineral carbonated concrete was lower than that of typical concrete with 30 MPa because carbonation increases strength while consuming less cement. The research further demonstrated that CO₂ might be efficiently sequestered by alkaline industrial waste. Since cutting carbon emissions might help to slow climate change, these discoveries may have substantial implications for the cement sector.

Kirchofer et al's [81] study investigated the impact of alkalinity sources on life cycle energy efficiency, as well as using minerals for aggregate in concrete production. They found that grinding, mixing, reaction yield, and heating were some of the environmental hotspots and that detailed simulations of these processes are needed for accurate comparison. Meanwhile, Pan et al estimated the worldwide sequestration potential of alkaline industrial wastes based on advances in their use for CO₂ sequestration. They calculated that 4.02 Gt CO₂ could be sequestered annually by carbonating alkaline industrial wastes globally.

Di Maria et al [82] conducted a study that compared carbonated steel slag blocks with PC blocks in terms of their environmental impact. The results showed that carbonated steel slag blocks might result in lower GHG emissions than PC blocks. However, despite the benefits of steel slag products, there is currently limited demand for them, which means other types of carbonated construction blocks need to be explored. Another study by Lee et al proposed the indirect carbonation of steel slag, which produces nano-sized calcium carbonates. Their LCA evaluation and economic analysis showed an eight percent reduction in net CO₂ emissions compared to conventional approaches.

To assess the environmental benefits of employing modified granulated copper slag (MGCS) in blended cement manufacturing, Zhang et al [83] using an LCIA model, evaluated the environmental effects of blended cement manufacturing with MGCS and compared it with the production of regular PC. In particular, global warming, which accounted for 93.67% of all impacts, was shown to be most affected by calcination, according to their data. The outcome of blended cement was dependent on the chosen LCIA model, the use of energy and limestone, and other factors. However, the use of MGCS in the manufacturing of blended cement assisted in reducing the environmental impact for all chosen impact categories, leading to a small rise in human toxicity by 6.52% and a reduction in abiotic depletion by 46.50%. According to the study's findings, employing MGCS in blended cement manufacturing can lessen cement production's total environmental impact and help the development of sustainable building materials. Reducing cement production's environmental effect is essential for reaching sustainable development objectives since it contributes significantly to GHG emissions, accounting for around 8% of worldwide CO₂ emissions.

To determine if blended cement might compensate for the loss of durability and CO₂ capture, García-Segura et al [84] undertook research to assess the environmental impact of blended cement. The study concentrated on the CO₂ emissions and capture for a reinforced concrete column both during and after its usage as gravel infill material. According to the research, utilizing PC mixed with fly ash (35% FA) and BFS (80% BFS) effectively reduced CO₂ emissions by 47%, 41%, and 20%, respectively. Although blended cement produces less CO₂ annually over a structure's lifespan, a high cement replacement might drastically shorten the service life. If the demolished concrete is recycled as gravel filler, carbonation can cut CO₂ emissions by half. The investigation concluded that while employing BFS can result in bigger reductions, substituting FA for PC can result in a lower material emission factor. These findings highlight the significance of utilizing blended cement in sustainable construction and the relevance of choosing the right blend depending on the processing needs and material availability in the area.

Magnesium is mainly produced in China by smelting dolomite, while magnesite is the primary raw material for making magnesia and magnesia masonry. Research shows that energy can be conserved in the manufacture of fused magnesia refractory materials [61]. However, studies have also found that magnesite mining can have negative environmental impacts, including soil contamination from magnesite dust [85] and groundwater contamination [86].

Another LCA study conducted by Li et al [61] investigated the environmental impact of different methods for producing fused magnesium oxide, considering the entire production process from raw material extraction to the final product. Their results revealed that the production process was the major contributor to all the environmental categories studied, mainly due to high energy consumption. According to research by Pan et al [87], reactive magnesium oxide may be manufactured utilizing rotary kilns with external heat sources and carbon dioxide recycling technology, which lowers CO₂ and SO₂ emissions.

In their study of a vertical kiln used to manufacture reactive magnesium oxide, Yue et al [88] looked at the impacts of utilizing dust removers, deterrents, and cleaner fuel sources, which resulted in a reduction in dust and SO₂ emissions. In the production of light calcined and sintered magnesia, Jing et al [89] emphasized the significance of reducing direct carbon emissions; however, for fused magnesia, the emphasis should be on reducing the carbon footprint associated with electricity consumption by increasing the thermal efficiency of heating furnaces.

Ruan and Unluer [90] compared the environmental impacts of producing reactive MgO cement to those of PC production in an LCA. The results of their study demonstrated that, when compared to the production of PC, the benefits of MgO production exceed the drawbacks of radiation, the ozone layer, eco-toxicity, acidification/eutrophication, minerals, and FF.

Hassan [91] has looked at the energy demand and CO₂ emissions linked to producing MgO cement and compared it to that of PC. The results show that the production of MgO requires more energy than PC due to several factors. The total energy required to acquire magnesite, the raw material used for MgO production, is higher than that required for limestone, the raw material used for PC production. Additionally, magnesite also has a higher work index value than limestone. Theoretically, a PC made from calcite has a lower energy need than MgO created via the dry and wet process pathways.

Magnesia production requires more energy than PC production, which increases CO₂ emissions. It was found that although the dry process for making PC releases around 1 tonne of CO₂ per ton of PC, the dry process to produce MgO releases approximately 1.7 tonnes of CO₂ per ton of MgO. However, studies have shown that MgO cement-based construction materials' curing processes may completely sequester the CO₂ generated during the calcining of magnesite[92]. Without incurring any additional expenditures, this technique reduces CO₂ emissions by 0.5–0.6 t/t on a net basis. The overall CO₂ emissions linked to the manufacture of PCs are around 40–50% more than this reduction in CO₂ emissions.

Contrarily, carbon capture and storage (CCS) technology used in the manufacture of PCs can lower CO₂ emissions. However, the cost of implementing CCS technologies is high, ranging from €41.2-53.8 /t CO₂, and regular maintenance is required. Additionally, the use of CCS can influence clinker properties, which can affect the quality of the final product [93].

1.11. Summary of the Literature Review

Finally, life cycle assessments are a key tool for assessing how products and processes may affect the environment. The environmental impact of the production of cement is being studied in several studies, but alternative cement still needs to be studied. A review of the literature suggests that the use of biomass for energy, mineral carbonation, and natural carbonation in the demolition of concrete can reduce carbon emissions in the cement industry. To reduce the environmental effects of cement production, further research is being conducted on the incorporation of other elements, such as alkaline industrial waste, carbonated steel slag, and modified granular copper slag. When selecting a specific mixture for the manufacture of mixed cement, it is crucial to take into account local material availability and processing needs. Magnesia cement, made from magnesium oxides found in magnesium silicates, is a promising alternative to PC due to its relatively low production temperatures and capacity to absorb CO₂. This study is aimed at comparing the environmental effects and benefits of producing magnesia cement incorporating the ÅA process with PC and a blended cement type (PSC).

2. Research Methodology

This study utilized the LCA methodology according to the International Organization of Standards (ISO) 14040:2007 and 14044:2007 [94] [95]. ISO 14040 offers the fundamental principles and framework for conducting and reporting an LCA, while ISO 14044 provides more specific procedures and examples, as well as guidelines for conducting an LCA. Using SimaPro 9.0 (PRé Sustainability), an LCA software, the environmental impacts of the production routes for magnesia cement, PSC, and PC were evaluated. To conduct an LCA study, there are four steps namely: Definition of goal and scope, life cycle inventory analysis, life cycle impact assessment, and interpretation [94]. The workflow model of the research methodology is presented in Fig. 8. Accordingly, this study was carried out in four stages :

1. Defining the scope and system boundaries for assessment.
2. Gathering inventory data which consists of inputs and outputs.
3. Evaluating the compiled environmental impact data in the inventory.
4. Interpreting the results of LCA and providing recommendations.

An additional step for sensitivity analysis of the results obtained from the lifecycle impact assessment was performed.

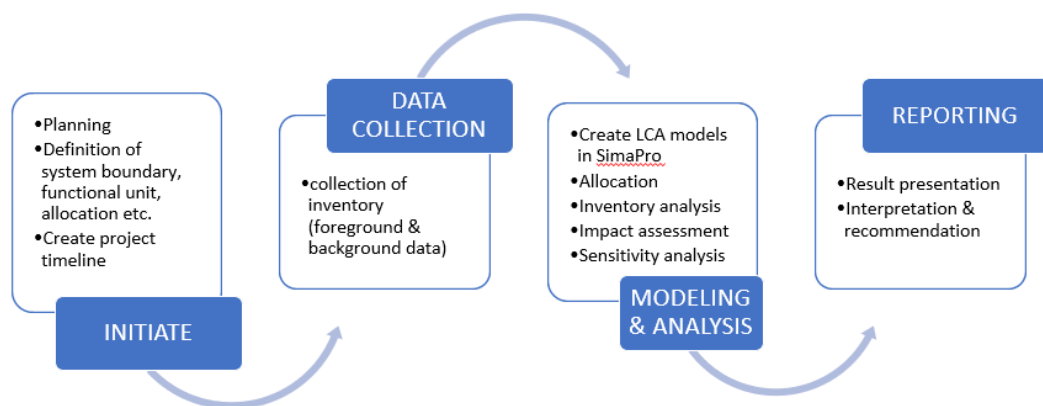


Fig.8. Workflow Model of Methodology

2.1. The Goal, Functional Unit, and Scope Definition

The focus and depth of an LCA study are mostly determined by the goal and scope of the study. Defining the goal of the LCA establishes the investigation's purpose, while the scope definition establishes the study's breadth and depth. The goal of the current study is to evaluate the environmental impacts of MgO cement production incorporating the ÅA process route and compare it with traditional PC production and PSC production. The research investigates the life cycle assessment of the primary processes involved in the production of each type of cement, from raw material acquisition to packaging the final product.

Fig. 9 illustrates the study's scope by defining the system boundaries that include the key processes involved in each material's production. There are at present three main types of boundary criteria that apply to the LCA of cement production: cradle-to-grave, cradle-to-cradle, and cradle-to-gate. When using the cradle-to-gate method, the assessment covers the time from the acquisition of raw materials

through the delivery of the cement for use. The LCA assesses the production of cement for the other two types from the point at which the raw materials are gathered from nature through to their eventual disposal and reuse in a new system. The cradle-to-gate boundary condition was selected for investigation in this study.

For the various types of cement, the comparative LCA process is often broken down into three stages: the raw materials acquisition, the manufacturing of clinker at the plant, and the grinding and crushing of the clinker. Gypsum is further added during PC and PSC manufacturing to regulate the setting of the cement in the third stage, and PSC also requires the addition of slag.

Based on the literature, the study's functional unit of assessment is one tonne of cement (MgO, PC, and PSC cement). The study's goal and scope definitions are critical to defining the research's objectives and ensuring that the research is comprehensive and focused.

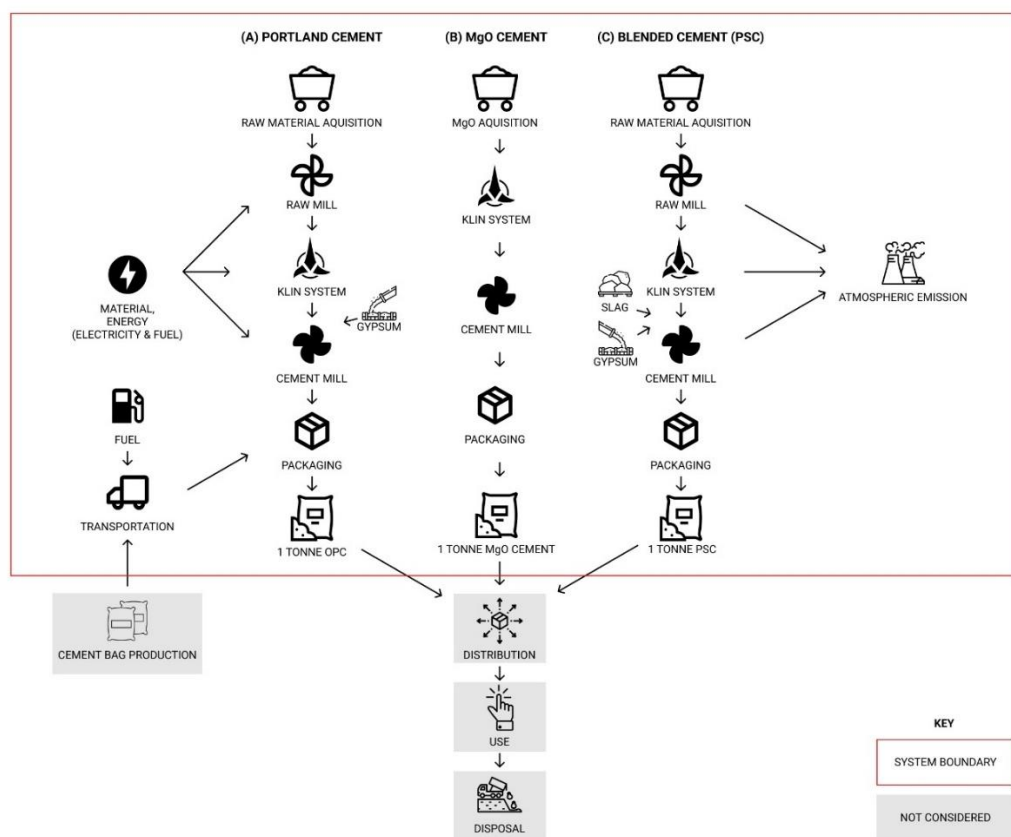


Fig. 9. LCA's scope illustrating the production processes for each of the cement types: (A) PC; (B) Magnesia cement; and (C) Blended cement (PSC).

2.2. Life-cycle Inventory Analysis (LCI)

The LCI phase is the second step in LCA, in which data is gathered to establish the model flows of a product system. A thorough list of measured fundamental flows that cross the system boundary of the life cycle is produced at this stage and is used as input for the following stage of the research. All input/output data, including raw materials, energy, and emissions, is gathered and evaluated to achieve the goal of the study. The LCI process is iterative, allowing for additional data to be added as the system is better understood during the modeling phase. This stage can be complicated and can involve several unit processes, such as raw material extraction, refining, and transportation of materials and products.

Table 2 presents data on input and emissions for each cement type being assessed. The two main inputs utilized in the production of PC are basic materials (such as limestone, clay, sand, iron ore, and gypsum) and energy sources (such as coal, fuel oil, petroleum coke, and electricity). PSC manufacture takes raw resources such as limestone, clay, laterite, slag, and gypsum as well as energy sources such as coal, electricity, and diesel, whereas the production of magnesia cement only needs one raw material (magnesite) and two energy sources (coal and electricity). Thermal energy is produced by the burning of coal, fuel oil, diesel, and petroleum coke and is used for raw material preparation, calcination, and transportation. Electric energy is produced through the usage of electricity generators.

Cement production requires a substantial amount of energy, and coal has frequently been the primary fuel used in cement kilns. About 450g of coal are required to manufacture every 900g of cement. Despite the fact that coal has historically been the primary fuel used in the cement industry, other fuels including gas, oil, liquid and solid waste, and petroleum coke have also been successfully used, either alone or in combination. Petroleum coke, a byproduct of crude oil production, is used in cement kilns all over the world. Due to difficulties with its burning, it is not always viable to employ 100% petcoke in cement kiln systems. It could be necessary to co-fire with a high-volatile fuel or take additional design considerations. When kiln waste heat is not available, fuel oil, a liquid petroleum product, is frequently used in auxiliary furnaces and kiln burners to dry raw materials and coal.

Excluding the materials that were put into the production process, the primary output of this study was found to be the emissions released into the air. The bulk of these emissions, which comprised carbon dioxide, carbon monoxide, SO₂, NO_x, and PM, were attributable to the calcination phase of the production of cement. The movement of raw materials and FF was assessed as part of the whole system, but because the effect was based on the distance between the cement factory and the producers, it was only given background consideration.

Table 2. Inputs and Emissions data for the cement types

	PC	Magnesia Cement	PSC
Basic Materials	Limestone	Magnesite	Limestone
	Clay	-	Clay
	Sand	-	Laterite
	Iron ore	-	Slag
	Gypsum	-	Gypsum
	Water	Water	Water
Energy	Coal	Coal	Coal
	Fuel oil	-	-
	Petroleum coke	-	-
	Electricity	Electricity	Electricity
	Diesel	Diesel	Diesel
Emissions	CO ₂	CO ₂	CO ₂
	SO ₂	SO ₂	SO ₂
	CO	CO	CO
	NO _x	NO _x	NO _x

	PC	Magnesia Cement	PSC
	Cement kiln dust	Magnesite dust	Cement kiln dust
	PM	Water vapor	PM

2.3. Life-cycle Impact Assessment (LCIA)

The LCIA step of an LCA entails converting the inputs and outputs of fundamental flows that were gathered and documented in the inventory into findings about their impact on human health, the environment, and resource depletion. It should be noted that LCA and LCIA generally analyze potential environmental impacts of actions affecting the natural environment and humans after the fate and exposure stage and can impact the interaction between technology and the environment. The LCIA results should be considered relevant indicators of potential environmental impacts rather than forecasts of definite environmental impacts.

Several impact assessment techniques are utilized to calculate impact assessment findings in the SimaPro software. The structure of these methods includes characterization, damage assessment, normalization, weighing, and addition (often referred to as single score). To evaluate the environmental impact of a product or service, a process of characterization is typically employed. This involves determining the contribution of each substance used in the production process and multiplying it by a factor that reflects its relative impact. The resulting figure provides a quantitative measure of the product or service's impact in each relevant impact category. During the damage assessment phase, the contributions of different materials and processes are expressed in a more general way based on the endpoint impact categories of the chosen impact assessment method. Normalization is the next step, which involves comparing the impact of the product or service to a reference value. This reference value is often the average environmental impact caused by one person in a single year. Finally, weighting is applied by multiplying the normalized indicators of each impact category by a weighting factor. This factor assigns higher importance to impact categories that are deemed to be more significant. The weighted results are converted into a single unit and added together to provide a single score. Finally, during the single score step, the normalized and weighted results are combined into a single score that represents the overall environmental impact [96]. Characterization is the obligatory element of the structure, while the other four steps are optional and may not always be available in all methods, as per ISO standards [94] [95]. In LCA, impact categories are used to assess the potential environmental impacts of a product or system throughout its life cycle. These categories are grouped into midpoint and endpoint categories. Midpoint impact categories assess how a system or product may affect a certain environmental indicator, such as the potential for eutrophication, acidification, or global warming. These categories include details on the nature and extent of the impact, but they do not explicitly assess how the impact may affect people's health or the environment [97]. On the other hand, endpoint impact categories are intended to assess the total environmental impact of a system or product on ecosystem quality, resource depletion, or human health. These categories frequently use midpoint indicators as well as other factors including toxicity, exposure, and risk assessment [97]. Endpoint indicators give a more detailed picture of the overall impact whereas midpoint indicators provide a direct measurement of a particular environmental impact. The selection between the endpoint and midpoint depends on the goal of the study and the amount of information necessary. Endpoint categories are more suitable for decision-making processes, whereas midpoint indicators are ideal for pinpointing particular areas for improvement [79].

The LCIA method used for this study is IMPACT 2002+. This method uses 14 midpoint categories to estimate a system's environmental effect. The four damage categories of human health, ecosystem quality, climate change, and resource depletion are then created from these midpoint categories. Every damage category takes different impacts into account. For instance, the category of Human health includes impacts like "Human toxicity," "Respiratory effects," "Ionizing radiation," and "Ozone layer depletion." "Ozone depletion", "Photochemical Oxidation", "Aquatic Ecotoxicity", "Terrestrial Ecotoxicity", "Aquatic Acidification", "Aquatic Eutrophication", "Terrestrial Acidification and Nitrification", and "Land Occupancy" are some of the impacts included in the Ecosystem Quality category. While the Resource Depletion category considers non-renewable energy consumption and mineral extraction, the Climate Change category assesses emissions that contribute to global warming [98].

These categories are measured using specific units. The Human health category is quantified in Disability Adjusted Life Years (DALYs), which represents the overall disease burden expressed as years lost due to ill health, disability, or death. The Ecosystem quality category is measured in Potentially Disappeared Fraction multiplied by area and years (PDF · m² · year), which represents the potentially disappeared fraction of species affected by toxins at certain concentrations. The amount of CO₂ that would have the same global warming impact as a certain gas combination is what is used to measure the climate change category in kilogram CO₂ equivalents. Finally, the Resource depletion category is measured in MJ primary energy [98].

To achieve consistent and equivalent outcomes in the LCA, the fundamental information from the Ecoinvent database was utilized for energy and transportation. Whenever possible, data that was extracted from the Åbo Akademi process route was given priority, but in cases where such information was unavailable, alternative sources such as scientific literature were utilized.

2.4. Interpretation

A vital step in determining how a product or service will affect the environment is the life cycle assessment's interpretation stage. Concluding the environmental performance of a product or service requires examining the findings of earlier LCA processes, such as inventory analysis and impact assessment. The interpretation stage aims to provide context for the results, identifying the key drivers of environmental impact and comparing the results to relevant benchmarks and standards [79]. The decisions made as a result of the findings obtained during the interpretation step include identifying areas for improvement and weighing various impacts on the environment. Understanding the data and assumptions underlying the LCA as well as the broader environmental, social, and economic context in which the product or service in question is being assessed is essential for effective interpretation.

2.5. Sensitivity Analysis (SA)

It is crucial to keep an LCA's limits in mind when you perform it. Due to the simplification of complicated issues, LCA studies include assumptions and scenarios that may not fully reflect real-world processes. Furthermore, it might not always be able to incorporate and assess all the required data throughout the study, which could lead to inaccurate information. Additionally, any errors or contradictions in the data utilized for the inventory may have a major impact on the analysis's results. To assess the reliability of the assumptions made and evaluate the influence of the parameters that are utilized on the LCA findings, a SA was carried out.

Sensitivity analysis, according to ISO 14044 [95], is a technique used in life cycle assessment (LCA) that seeks to identify and quantify the impacts of variations in the LCA data, assumptions, or models on the assessment's results. Therefore, the purpose of the SA is to evaluate and improve the robustness of the results of a study and conclusions by identifying how potential uncertainties may impact those conclusions [95]. One method for doing SA is to gradually adjust the input parameters of the LCA model and analyze how the results of the LCA change as a result of the modifications [99]. This makes it possible to examine the impact of data uncertainty and variability as well as to identify the factors that have the most impact on the results.

To ensure the credibility and transparency of the results, ISO 14044 advises that SA be carried out as part of the LCA study. However, the failure of a SA to demonstrate significant differences between studied alternatives does not imply that there are no differences, only that they are not significant [99]. The associated hotspots for the production of the three types of cement will be determined for the SA of this research when the LCIA results have been obtained. Next, the input parameters will be gradually changed. The resulting changes as a result of the alteration will then be assessed.

3. Research Results & Discussion

3.1. Life Cycle Inventory (LCI) Results

To illustrate the amount of raw materials needed to produce 1 tonne of each type of cement, material flow diagrams were made, detailing the steps at which each item is used. Additionally, process flow diagrams were generated to illustrate the sequence of operations involved in producing each cement type, along with the corresponding inputs (such as energy/heat) and outputs (such as emissions) linked to each step.

The material and process flow diagrams of MgO cement, PC, and PSC production processes are shown in Fig. 10, 11, and 12, respectively. The diagrams illustrate that magnesia cement is produced using a single ingredient, magnesite, making the acquisition of raw materials simpler than PC and PSC production, which require multiple raw materials. Additionally, the study notes that raw materials for PC and PSC are obtained through mining, while the acquisition of magnesite, as considered in this study, is through the AA process route.

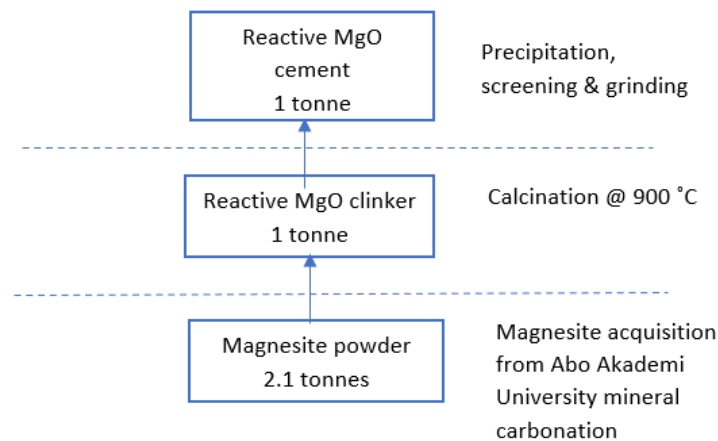


Fig. 10a. MgO cement material flow diagram [49]

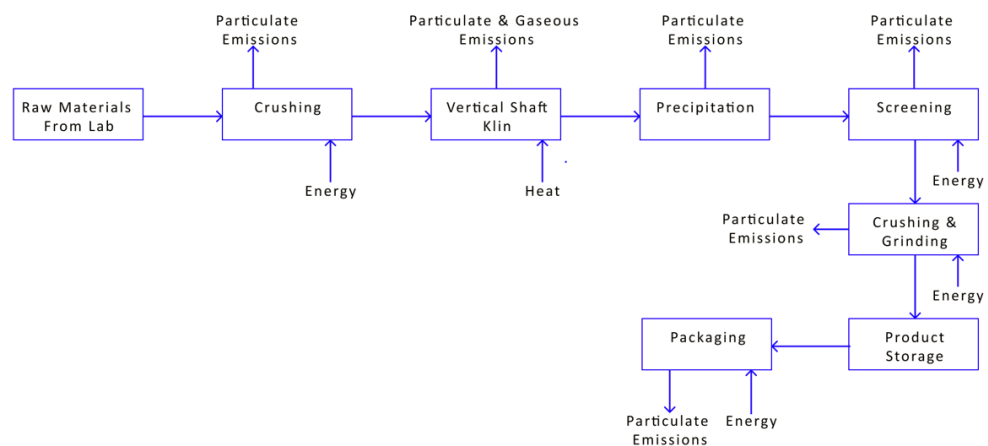


Fig. 10b. Flow diagram of the production process of MgO cement displaying the energy and heat input as well as emissions produced. (Magnesite from the AA process route replaces magnesite extraction via mining).

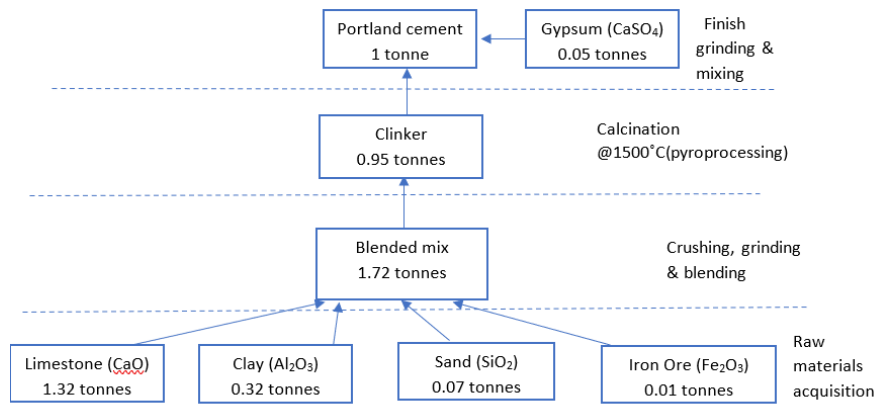


Fig. 11a. OPC material flow diagram [66] [83]

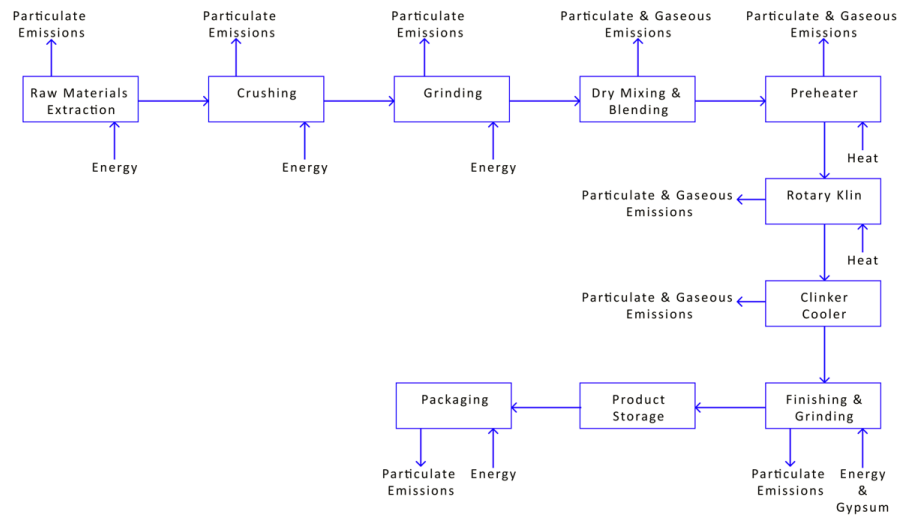


Fig. 11b. Flow diagram of the production process of OPC displaying the energy and heat input as well as emissions produced

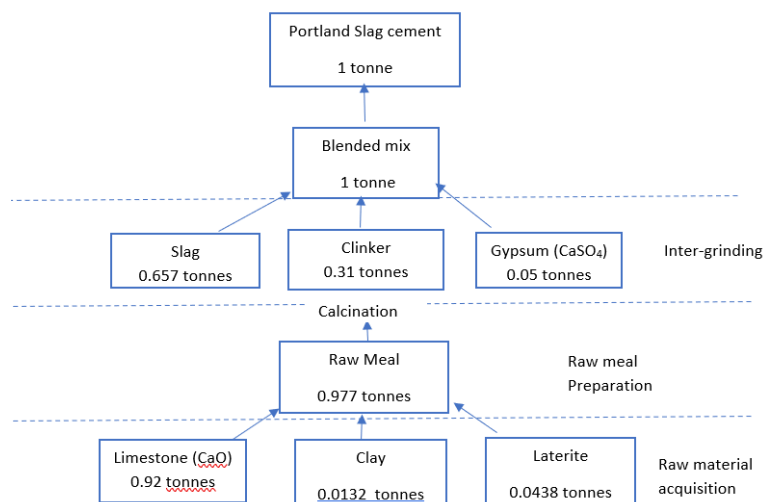


Fig. 12a. PSC material flow diagram [66] [83]

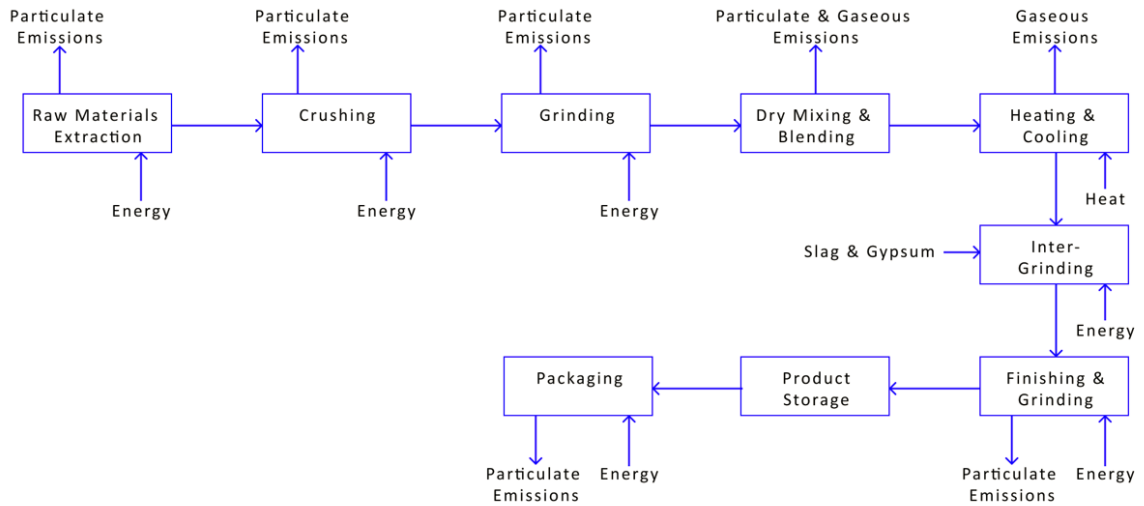


Fig. 12b. Flow diagram of the production process of PSC displaying the energy and heat input as well as emissions produced

The tables presented below display the outcomes of the inventory analysis, with the quantities of raw materials listed reflecting the typical amounts necessary for producing one tonne of each cement type, as indicated by the material flow diagrams.

Table 2 provides inventory data for producing one ton of PC, which is an average value obtained from various cement plants in the European Union, based on information from the BAT document [66] and adapted from literature [49]. Table 3 shows input and emission data for producing one ton of reactive MgO, derived from supporting information provided in [61], while Table 4 presents input and emission data for producing one ton of PSC, based on information from [83]. The inventory data for raw material acquisition and energy use for various processes were gathered from the SimaPro database. SimaPro has direct integration with well-known databases such as the Ecoinvent database, which is a valuable source of data on cement and concrete production and is frequently utilized in the environmental sector. The PSC and magnesia cement inventories represent the average values of plants in China for producing one ton of each cement type.

Table 3. Inventory data for the production of PC using the defined FU [49] [66]

	Inputs/Emissions	Amounts
Basic Materials	Limestone (tonne)	1.32
	Clay (tonne)	0.32
	Sand (tonne)	0.07
	Iron ore (tonne)	0.01
	Gypsum (tonne)	0.05
	Water (tonne)	0.53
Energy	Coal (tonne)	5.53E-9
	Fuel oil (tonne)	1.53E-9
	Petroleum coke (tonne)	0.1
	Electricity (kWh)	71.92
	Diesel (tonne)	9.00E-7

	Inputs/Emissions	Amounts
Emissions	CO ₂ (kg)	832.61
	SO ₂ (kg)	0.63
	CO (kg)	1.96
	NO _x (kg)	1.79
	Cement kiln dust (kg)	0.87
	PM (kg)	0.03

Table 4. Inventory data for the production of magnesia cement using the defined FU [61]

	Inputs/Emissions	Amounts
Basic Materials	*Magnesite (tonne)	2.17
	Water (tonne)	0.01
Energy	Coal (tonne)	0.27
	Electricity (kWh)	8.67
	Diesel (tonne)	0.54
Emissions	CO ₂ (kg)	1096.54
	SO ₂ (kg)	4.21
	CO (kg)	0.02
	NO _x (kg)	0.01
	Water Vapor (m3)	0.01
	Magnesite dust (kg)	0.99

Note: SimaPro 9.0 (PRé Sustainability) does not have an inventory for magnesite, thus dolomite was used instead. Magnesium oxide, the main component of magnesia cement, may be found in dolomite and magnesite.

Table 5. Inventory data for the production of PSC using the defined FU [83]

	Inputs/Emissions	Amounts
Basic Materials	Limestone (tonne)	0.92
	Clay (tonne)	0.0132
	Bauxite (tonne)	0.0438
	Slag (tonne)	0.00031
	Gypsum (tonne)	0.05
	Water (tonne)	0.53
Energy	Coal (tonne)	4.49E-9
	Diesel (tonne)	2.23E-9
	Electricity (kWh)	68.37
Emissions	CO ₂ (kg)	684
	SO ₂ (kg)	0.1
	CO (kg)	1.22
	NO _x (kg)	0.62

	Inputs/Emissions	Amounts
	Cement kiln dust (kg)	0.76
	PM (kg)	0.03

3.2. Life Cycle Impact Assessment (LCIA) Results

This section starts by presenting the LCIA results for each type of cement. The analysis of the characterization results for the various types of cement, as indicated in the methodology chapter, is obligatory. This chapter also includes the interpretation of the characterization, damage assessment as well as normalization results of the comparative analysis are also presented in this chapter.

The characterization results of the impact assessment employing the IMPACT 2002+ method are illustrated for the functional unit of study for each of the types of cement in Figures 13, 14, and 15, respectively. The graphs show the relative contribution of the different components/inputs to produce each cement towards the impact categories. A further classification of human toxicity into carcinogens and non-carcinogens resulted in the 15 impact categories that are presented:

1. **Carcinogens:** evaluates the likelihood of a substance to result in cancer in people or animals.
2. **Non-carcinogens:** evaluates a substance's potential to have non-cancerous health impacts, such as neurological or respiratory issues.
3. **Respiratory inorganics:** evaluates a substance's ability to induce respiratory issues by inhalation, such as lung irritation or injury.
4. **Ionization radiation:** analyzes a substance's ability to emit ionizing radiation, which may be harmful to both human health and the environment.
5. **Ozone Depletion:** determines how much a material can harm the ozone layer, which increases the risk of skin cancer and other health problems.
6. **Respiratory organics:** evaluates how likely a substance is to induce respiratory issues like asthma or bronchitis through inhalation
7. **Aquatic ecotoxicity:** evaluates if a material has the potential to harm aquatic species like fish or algae when exposed to water, through the release of toxic substances into water bodies.
8. **Terrestrial ecotoxicity:** evaluates if a substance has the potential to harm terrestrial species like plants or insects when exposed to soil and vegetation.
9. **Terrestrial acid/Nutri:** evaluates a substance's potential to cause nutrient depletion or soil acidity, which can be detrimental to plant development and biodiversity.
10. **Land Occupation:** evaluates a system's or product's potential impact on the use of land resources, which might have detrimental effects on ecosystems and biodiversity.
11. **Aquatic acidification:** Assesses the possible influence of a product or process on the acidity of aquatic habitats.
12. **Aquatic eutrophication:** evaluates a product's or process's possible impact on the development of algae and other aquatic plants in water bodies, which can lower oxygen levels and endanger aquatic life.
13. **Global warming:** evaluate a product's or process's possible impacts on climate change, in particular on the GHG emissions that contribute to the planet's warming
14. **Non-renewable energy:** The potential for a system or product to use non-renewable resources, such as FF, which can contribute to climate change and the depletion of natural resources, is evaluated in this impact category.

15. **Mineral extraction:** evaluates the potential for a product or system to contribute to the exploitation and depletion of mineral resources, which may have detrimental effects on the environment and communities near it.

3.2.1. Magnesia Cement

As illustrated in Fig. 13, electricity has the biggest impact on carcinogens, non-carcinogens, ionizing radiation, aquatic ecotoxicity, land occupation, aquatic eutrophication, non-renewable energy, and mineral extraction category. In the respiratory inorganics, aquatic acidification, and global warming categories, the graph indicates that magnesia cement contributes over 95% of the impact to these categories. The impact of diesel is most significant in the respiratory organics category, with notable impacts in ozone layer depletion and carcinogens categories.

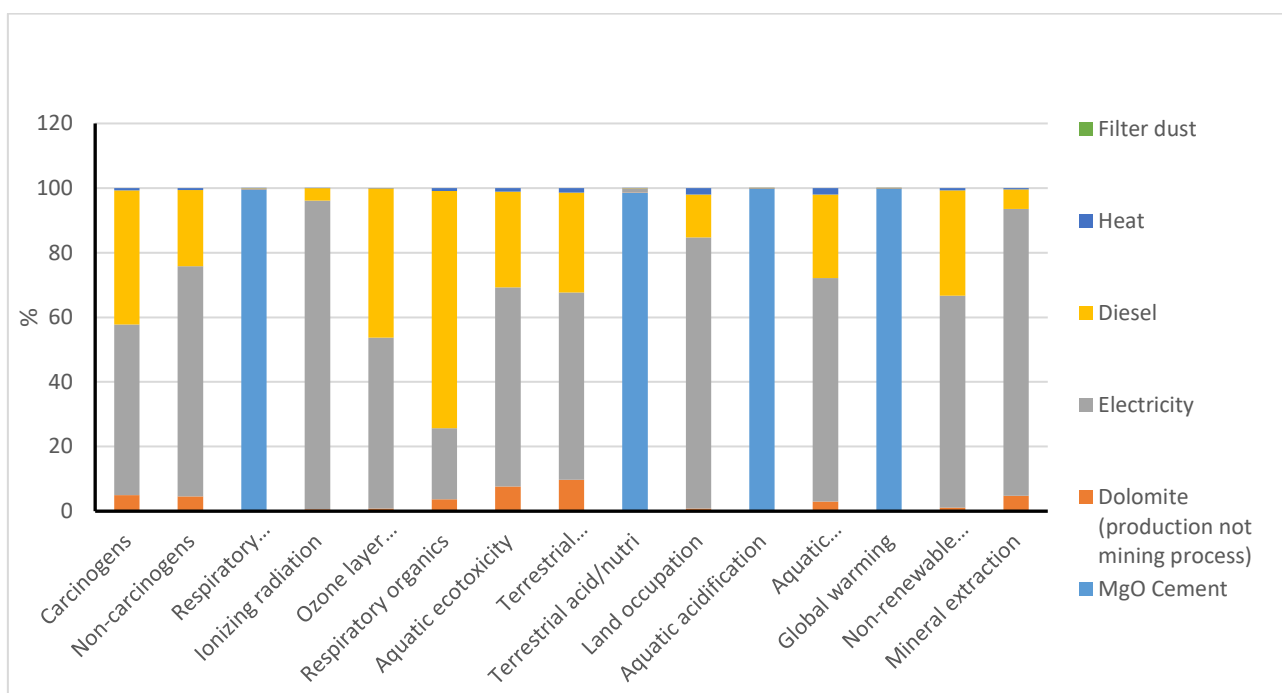


Fig. 13. Magnesia cement characterization results using IMPACT 2002+ Method

According to the results, electricity has the most contribution to the majority of the impact categories considered for magnesia cement. The burning of FF to produce power could be linked to cancer-causing effects because it generates air pollutants and GHG [100]. Due to the same cause, non-carcinogenic effects are also common and can harm the ecosystem by causing eutrophication, ozone depletion, and acidification. The production of electricity using fuels containing radioactive elements may be the cause of the significant effects as seen in the ionizing radiation category. Pollutants released during the burning of fuel and electricity can also be hazardous to aquatic life. High impacts on land occupation could likely be caused by the demand for land to construct power plants and transmission infrastructure.

The considerable impact seen in the respiratory inorganics category may be caused by the release of inorganic particles such as silicon dioxide, magnesium oxide, and other trace elements during the production process of MgO cement [50]. This can have detrimental impacts on people's health and their surroundings, underscoring the need of having effective management and control over the manufacturing processes.

The considerable impact on the aquatic acidification category is probably caused by the release of carbon dioxide during the chemical processes involved in the manufacturing of magnesia cement, which contributes to the acidification of aquatic habitats [50]. The energy-intensive manufacturing process for MgO cement also has a major adverse impact on global warming, principally because it uses a lot of FF and emits CO₂.

3.2.2. Portland Cement

From Fig. 14, we can identify the components/inputs that have the biggest impact on the different categories in the production of PC. As in the case of magnesia cement, electricity has a significant impact in all of the impact categories, and as discussed, this impact may likely be attributed to the burning of FF. Petroleum coke also used as a source of energy in cement production, also contributes to the impact of ozone layer depletion, respiratory organics, ionization radiation, non-renewable energy, carcinogens, and non-carcinogens according to the graph.

Pollutants such as NO_x, SO₂, and PM are released during the combustible process of petroleum coke, and these pollutants harm human health as it relates to carcinogenic and non-carcinogenic impacts as well as contribute to ozone depletion when cement is produced [101]. Additionally, the combustion process may produce traces of naturally existing radioactive elements, which may be responsible for the impact in the ionizing radiation category. In addition, the burning of petroleum coke releases polycyclic aromatic hydrocarbons and volatile organic compounds which may be attributed to the impact on respiratory organics [102]. Finally, the utilization of petroleum coke as a fuel source in the production of cement may contribute to the depletion of non-renewable energy supplies because it is a non-renewable resource. This major impact can be because PC production consumes a significant amount of energy, including raw material extraction and transportation, kiln heating, and finished product grinding.

The graph also indicates that limestone and clay have a major impact on the carcinogens, non-carcinogens, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, land occupation, and mineral extraction impact categories. When these materials are heated and ground, dust containing heavy metals and other pollutants that might be harmful to human health is released, which is likely the reason for the impacts seen in the categories of human toxicity (carcinogens & non-carcinogens). Additionally, respiratory organics could be impacted by the energy needed to extract and refine these raw materials. Due to the potential release of heavy metals, sulfate, and chloride during extraction and processing, limestone may have a high impact on aquatic ecotoxicity [103]. The significant impact on terrestrial ecotoxicity as seen could be due to the extraction and transportation processes, which could cause soil erosion, habitat destruction, and the loss of vegetation and biodiversity. The usage of large machinery during the manufacturing of clay and limestone may also be responsible for the high impact on mineral extraction.

PC itself is the main contributor to the respiratory inorganics, terrestrial acid/nutri as well as global warming categories, accounting for 66.3%, 85.5%, and 93.4% of impact in these categories respectively. The grinding and heating of raw materials involved in the production process of PC can release dust and other pollutants into the air, which could contribute to the respiratory inorganics impact. The emission of CO₂ during the manufacturing process can also cause soil acidification and nutrient depletion [104], which may have influenced the significant impact in the terrestrial acid/Nutri

category. Finally, the high temperature required in the kiln for clinker formation is the major source of the impact of global warming [1].

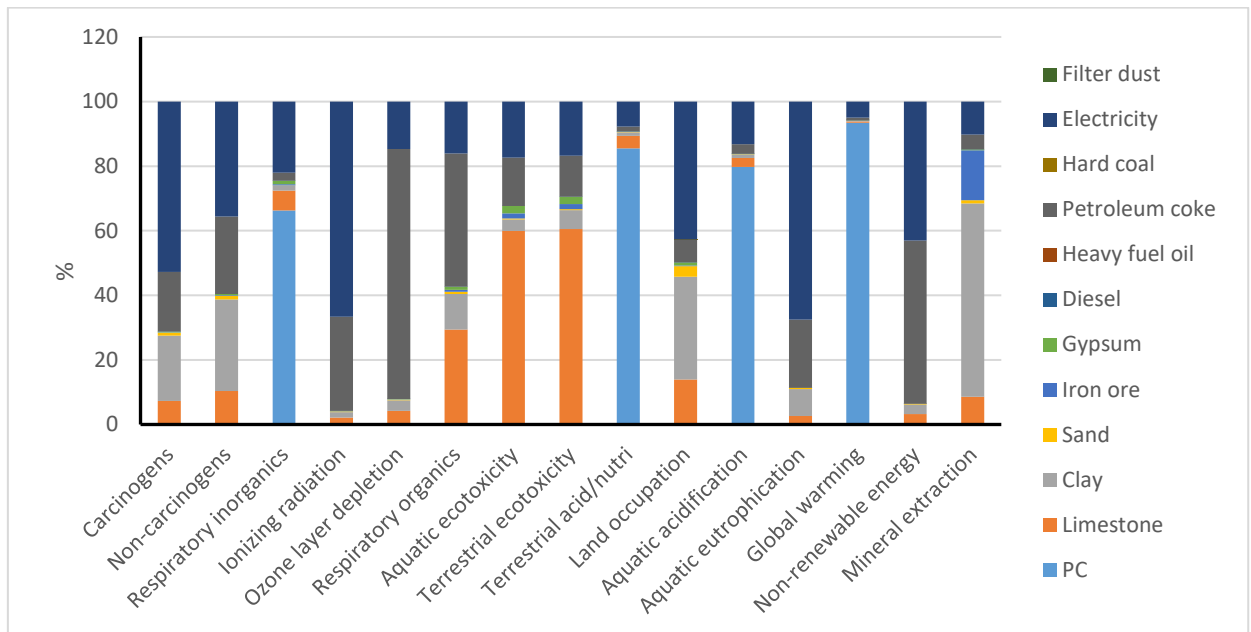


Fig. 14. PC characterization results using IMPACT 2002+ Method

3.2.3. Portland Slag Cement

The component/input with the most significant impact in most of the categories is electricity as observed in Fig. 15. This, like the other cement types, may be linked to the FF used to provide the energy needed for PSC manufacturing.

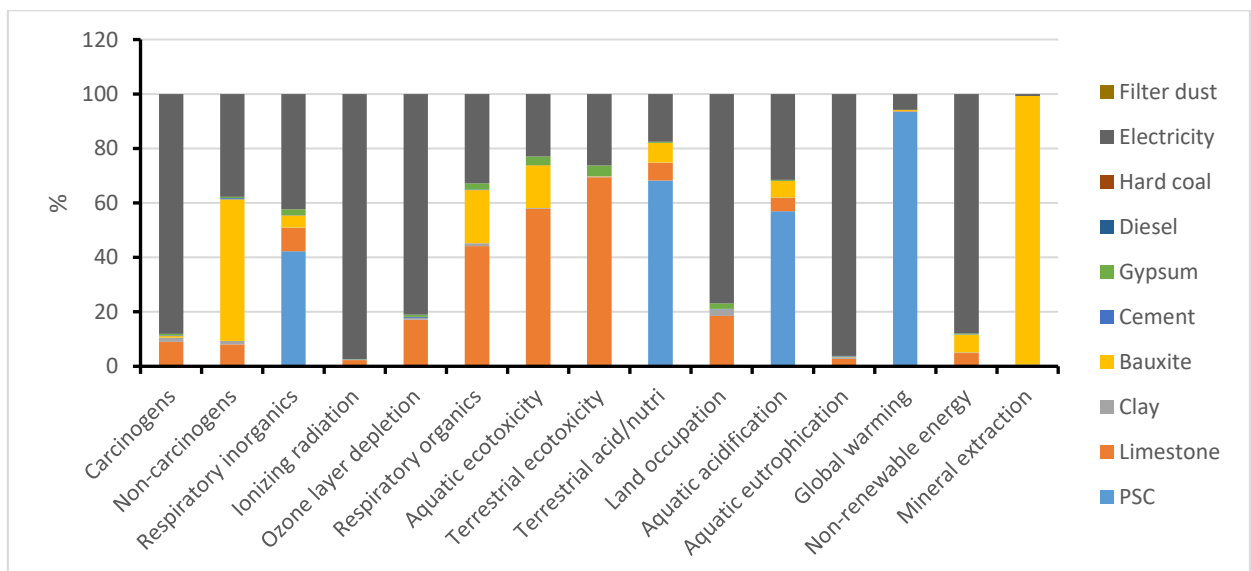


Fig. 15. PSC characterization results using IMPACT 2002+ Method

With a relative contribution of 51.9% to the non-carcinogens category and 98.7% to the mineral extraction category, respectively, bauxite is the main contributor to these categories. Both positive and negative effects may be attributed to using bauxite as a raw material for PSC manufacture. On the one hand, it gives cement manufacturers a crucial source of aluminum [105]. However, the mining and exploitation of bauxite may have some negative impacts. Mining operations generally have the

potential to cause deforestation, biodiversity loss, and soil erosion. Bauxite poses a threat to the environment by polluting groundwater and fertile soil considering its highly alkaline and caustic content [106]. Likewise, non-carcinogenic particles that might be released into the air and water during the mining and extraction of bauxite, and human health hazards from bauxite's caustic (NaOH) concentration include skin issues and eye irritation [106].

In the respiratory organics, aquatic, and terrestrial ecotoxicity categories, limestone is the major contributor, with the relative contribution of 44.2%, 57.9%, and 69.4% respectively. Bauxite also has notable impacts in these categories. The impact in these categories could be due to several implications that may arise from using these raw materials in the production of PSC. For instance, People nearby the vicinity may experience respiratory issues as a result of dust and particle matter released into the air during limestone mining, crushing, and processing. The impact of the aquatic ecotoxicity category may also be attributable to the discharge of sediment and other pollutants into neighboring waterways as a result of the mining and processing of limestone. The extraction and processing of bauxite can also lead to marine contamination through the release of red mud, which may include heavy metals and other pollutants, as well as respiratory issues because of the release of dust and other particulates.

From the graph, it can also be identified that PSC contributes much of the impact to the respiratory inorganics, terrestrial acid/nutri, and global warming categories. When breathed, inorganic compounds such as PM, SO₂, NO_x, and CO that are released throughout the manufacturing process might cause respiratory health issues. PSC's composition and energy-intensive manufacturing process can also be attributed to its significant effect in the terrestrial acid/nutri category. PSC is manufactured from clinker, BFS, and gypsum and heated at high temperatures in a kiln, emitting carbon dioxide into the atmosphere and causing global warming, as was already mentioned in the previous chapter. Therefore, the high carbon dioxide emissions from PSC's production process may be used to explain its significant impact on the global warming category.

A more visual representation of the hotspots identified during the production of each cement type is given in the network flow chart in Fig. 19, 20, and 21 respectively in Appendix 1.

3.2.4. Comparative Analysis of Magnesia, Portland & Portland Slag Cement

The comparative analysis for the three types of cement was also performed in SimaPro 9.0 using the IMPACT 2002+ method, in this section, the characterization and normalization results are presented. The results of the damage assessment are presented in Fig. 22 and Table 7 of Appendix 1 and Appendix 2 respectively.

Characterization: Fig. 16 shows the characterization results of the individual impact categories for the production of each cement type. From the graph, we can observe that PC has the greatest impact in 13 out of 15 of the impact categories namely carcinogens, non-carcinogens, respiratory inorganics, ionization radiation, ozone layer depletion, respiratory organics, aquatic ecotoxicity, terrestrial ecotoxicity, terrestrial acid/nutri, land occupation, aquatic eutrophication, global warming, and non-renewable energy.

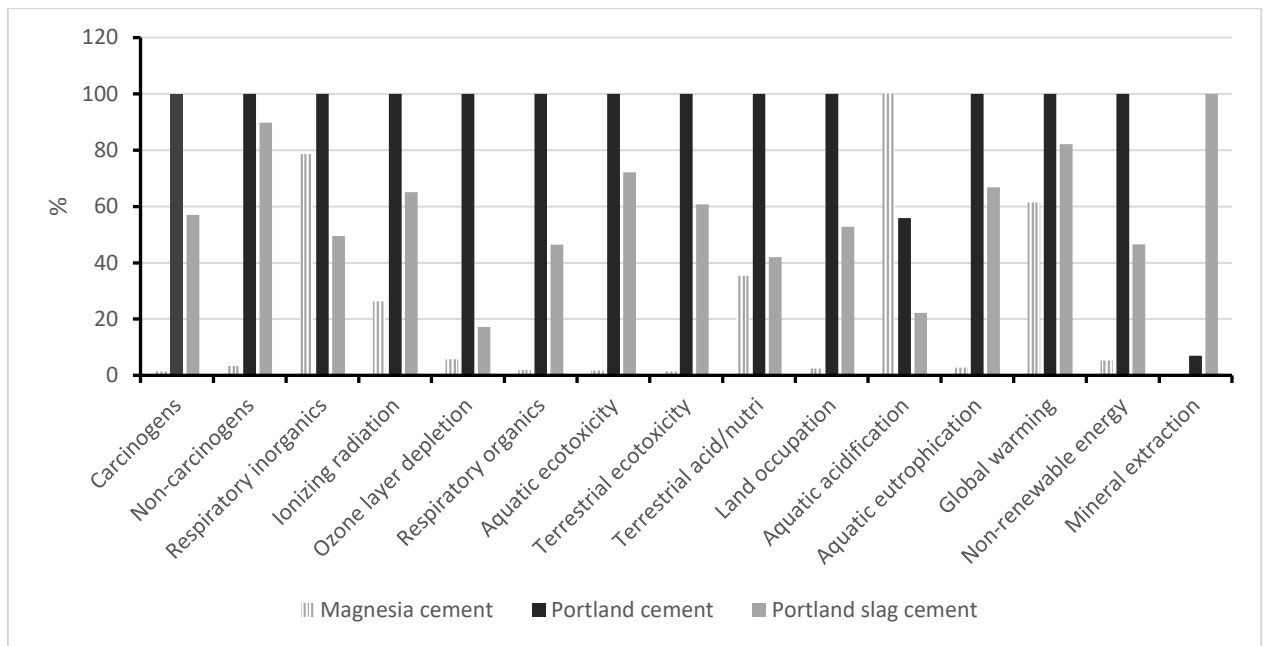


Fig. 16. LCIA characterization results for the comparative analysis of Magnesia, Portland, and PSC.

The impact of PC is approximately 50 times more than the impact of magnesia cement and approximately 2 times bigger than the impact of PSC when it comes to the carcinogens category (PC is 99%, MgO cement is 2%, and PSC is 57%). In the non-carcinogens category, the impact of PC is roughly 33 times more than the impact of magnesia cement and approximately 1 time larger than the impact of PSC (PC is 99%, MgO cement is 3%, and PSC is 89%). The impact of PC is about 1.2 times bigger than the impact of magnesia cement and nearly 2 times higher than the impact of PSC in the respiratory inorganics category (PC is 99%, MgO cement is 78%, and PSC is 49%). In terms of ionizing radiation, PC has a roughly 4 times stronger impact than MgO cement and a roughly 1.5 times greater impact than PSC (PC is 99%, MgO cement is 25%, and PSC is 65%). PC has an impact that is about 20 times more than that of magnesia cement and about 6 times higher than that of PSC in the ozone layer depletion category (PC is 99%, MgO cement is 2%, and PSC is 17%). The impact of PC is approximately 49.5 times bigger than the impact of magnesia cement and approximately 2.1 times more than the impact of PSC in the respiratory organics (PC is 99%, MgO cement is 2%, and PSC is 46%). For the aquatic ecotoxic category, the impact of PC is about 49.5 times greater than the impact of magnesia cement and about 1.3 times greater than the impact of PSC (PC is 99%, MgO cement is 2% and PSC is 73%). In the terrestrial ecotoxicity category, the impact of PC is approximately 49.5 times more than the impact of magnesia cement, and approximately 1.7 times bigger than the impact of PSC (PC is 99%, MgO cement is 2%, and PSC is 60%). When it comes to the terrestrial acid/nutri category, PC has an impact that is approximately 2.8 times bigger than that of magnesia cement and approximately 2.3 times higher than that of PSC (PC is 99%, MgO cement is 3%, and PSC is 43%). The impact of PC is approximately 33 times bigger than the impact of magnesia cement in the land occupation category and approximately 1.7 times greater than the impact of PSC in the terrestrial acid/nutri category (PC is 99%, MgO cement is 3%, and PSC is 57%). The impact of PC is approximately 49.5 times bigger than the impact of magnesia cement for the aquatic eutrophication category and approximately 1.4 times more than the impact of PSC for the terrestrial acid/nutri category (PC is 99%, MgO cement is 2%, and PSC is 72%). When it comes to the global warming category, PC has a 1.7 times bigger impact than magnesia cement and a 1.2 times bigger impact than PSC (PC is 99%, MgO cement is 60%, and PSC is 80%). In the non-renewable energy

category, the impact of PC is around 19 times bigger than the impact of magnesia cement, and approximately 2.2 times larger than the impact of PSC in the terrestrial acid/nutri category (PC is 99%, MgO cement is 5%, and PSC is 45%). The production process of PC, which produces considerable amounts of air pollutants such as VOCs, NO_x, SO_x, and heavy metals, may be the main cause of the cement's significant impact on these categories. Additionally, the production process emits naturally occurring radioactive substances as well as chlorofluorocarbons (CFCs), which can cause lung cancer and deplete the ozone layer. The results demonstrate that all three types of cement greatly impact the category of global warming. The impact in this category may be due to the GHG emissions caused by the cement types' production processes, particularly CO₂. Because they use alternative raw materials and require less energy during production, the results also demonstrate that magnesia cement and PSC have less of an impact on the environment than PC in some areas, such as global warming.

Additionally, results indicate that PSC and magnesia cement have the greatest impacts on mineral extraction and aquatic acidification, respectively. Magnesia cement has an impact that is 1.8 times bigger than that of PC and almost 4.5 times more than that of PSC in the aquatic acidification category (MgO cement is 99%, PC is 55%, and PSC is 22%). The impact of PSC is approximately 99 times bigger than the impact of magnesia cement and approximately 14 times greater than the impact of PC in the category of mineral extraction (PSC is 99%, MgO cement is 1%, and PC is 7%). Magnesia cement may have a considerable negative impact on the impact category for aquatic acidification due to the significant SO₂ emissions that were noted in the inventory data during manufacture and may contribute to acid rain and harm aquatic ecosystems. Compared to PSC, PC has a greater environmental impact, probably as a result of increased SO₂ and NO_x emissions, which are seen in the inventory data. The lower impact of PSC could be because it uses ground granulated BFS, which has a lower sulfur and nitrogen content. Because slag is a by-product of the steel industry and requires a large amount of raw materials to produce, PSC has a high impact on the category of mineral extraction. Significant quantities of iron ore and other minerals, which are obtained through the process of mining, are needed to produce slag. Therefore, the high impact of PSC on the mineral extraction impact category could be an indirect impact from steel production. The process by which magnesite was obtained may be responsible for the relatively minor impact of magnesia cement in the mineral extraction category. Because it is assumed in this study that the raw materials for PC and PSC were mined, whereas magnesite was obtained as a byproduct of the AA process.

It is important to remember that the processes of production and raw material sources employed in this study might have impacted the results. The details of the LCIA characterization results have been presented in Table 8 of the appendices.

Normalization: After evaluating the life cycle impacts of the three types of cement, the results were normalized. Four damage categories are identified in this case: human health, ecosystem quality, climate change, and resources. The units of measurement are unified once results have been normalized so that it is possible to compare each cement's impacts between the various categories. According to the graph in Fig. 17, which shows the normalized results for the various categories, PC has the most impact on all four categories. PC has most of the impact on human health; it is about 22.3% greater than that of magnesia cement and about 50.5% greater than that of PSC, making PSC the cement in this category with the least impact. According to the graph, magnesia cement has only a small impact on ecosystem quality, but PC's impact is almost 46.7% bigger than PSC's. In terms of climate change, PC has an impact that is about 38.6% more than that of magnesia cement and around

17.8% greater than that of PSC. According to the graph, the impact of magnesia cement is similarly quite small in the resources category, although the impact of PC is approximately 52% more than that of PSC.

The impact category most affected by the production of each cement type is the climate change category as indicated in Fig. 17. However, each cement type performs better in the ecosystem and resources category, in comparison to the human health and climate change categories. The impact of magnesia cement in the climate change category is about 46.7% greater than the human health category. The impact of PC in the climate change category is higher than in the human health, ecosystem quality, and resources categories with about 58%, 97%, and 90% respectively. The impact of PSC on the climate change category is about 74.7% greater than the human health category, about 98% greater than the ecosystem quality category, and about 94.2% greater in the resources category.

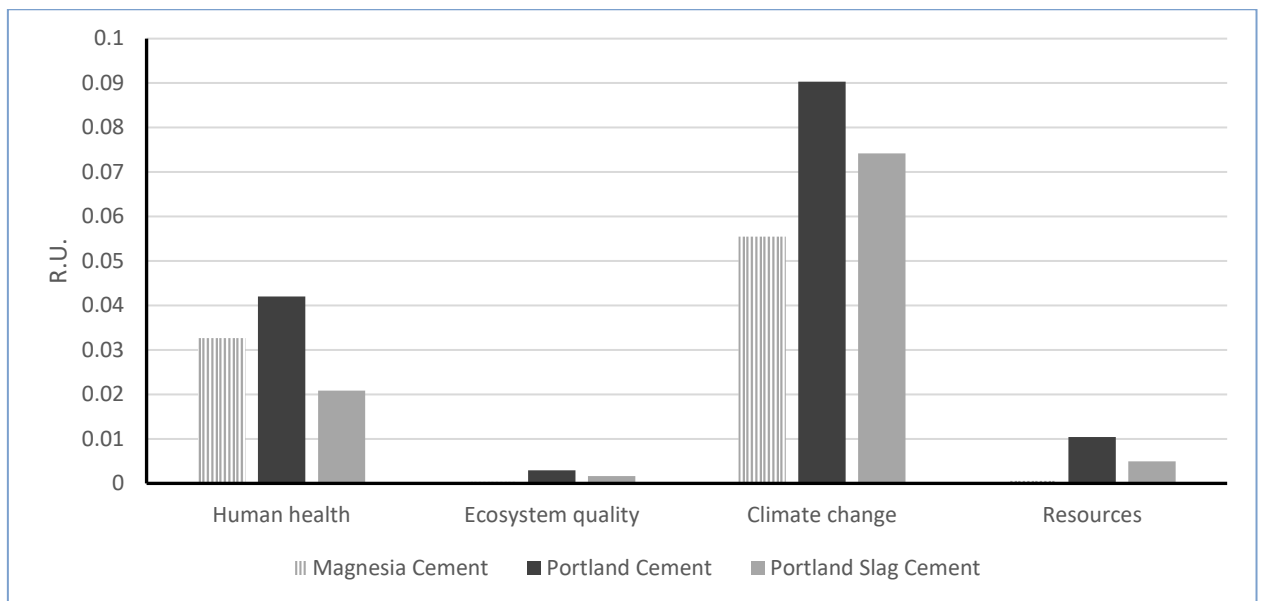


Fig. 17. LCIA normalization results for the comparative analysis of Magnesia, Portland, and PSC.

3.2.5. Results Comparison with Other Studies

When performing a life cycle assessment, it is difficult to directly compare the results with the works of different authors because not only the goals of the work or the products being compared may differ, but also the functional unit, system boundaries, and the impact assessment calculation method. These factors greatly influence the results of an LCA study and their comparability. Due to these factors, even if the products are the same, their relative contributions obtained in different categories may not be comparable. Since no single study compared all three types of cement analyzed in this study, the comparison with existing studies was first done as magnesia cement and PC, followed by a separate comparison between PC and PSC.

Ruan and Unlucer [90] conducted a life cycle assessment to evaluate the environmental impacts of magnesia cement production to PC production, as was previously discussed in the literature review chapter. Using SimaPro 7.0, the research was carried out, and the cradle-to-gate LCA of the primary processes was examined. This involved important environmental processes from acquiring basic materials to the packaging of the completed product. One tonne of cement served as the functional unit of evaluation. The impact assessment calculations used the Eco-indicator 99 method, and the outcomes presented a comparison of the cement types in 11 impact categories. Their findings show

that the production of magnesia cement creates a higher percentage of carcinogens and has more of an impact on climate change when compared to PC production. They did, however, go on to note that studies investigating the usage of magnesia cement in concrete materials have shown that formulations consisting of magnesia cement can entirely carbonate and achieve a carbonation level of 100%. Also, when the carbonation capacity of magnesia cement was factored into the total emissions computation, the CO₂-eq of magnesia cement was found to be up to 73% lower than PC, with a net amount after carbonation of 264 kg CO₂-eq. Furthermore, the results compare the three damage categories of human health, ecosystem quality, and resources. According to their findings, magnesia cement had an edge in the ecosystem quality and resources category but had the greatest impact on the human health category. This study obtained slightly different results, magnesia cement had the least impact in the damage categories except the human health. However, PC had the biggest impact in the human health category, making PSC the least contributor to this category. The findings of this study indicate that all three types of cement had a considerable influence on climate change; however, when compared, magnesia cement had the least. This variation in outcomes could be explained by the method used to get the basic material magnesite. Based on this research, it was assumed that magnesite was a byproduct of the Abo Akademi method for staged carbonation of magnesium silicate-based rock, whereas, in their study, magnesite acquisition was through mining. Because the magnesium-based silicate rock can be crushed and ground using less energy-intensive machines, the Abo Akademi process uses less energy than mining and processing raw magnesite. Additionally, by using carbon dioxide from industrial processes or other sources to react with the magnesium silicate-based rock, the Abo Akademi process has the potential to lessen the carbon footprint of magnesite production. On the other hand, the mining and processing of raw magnesite frequently demand large energy inputs and might result in GHG emissions.

Additionally, there are some parallels between these works, and the findings demonstrate that magnesia cement outperforms PC in the categories of ionization radiation, ozone layer depletion, terrestrial eco-toxicity, terrestrial acidification/Nutri, mineral extraction, and non-renewable energy.

Zhang et al [83] looked at the environmental advantages of producing blended cement with MGCS as opposed to regular PC. The study's functional unit was 1 kg of cement, and its system boundary condition relied on a cradle-to-gate perspective. Since they viewed the original copper slag preparation as a waste product with no environmental burden by EU directives, they did not take it into account in their study. They just took into account the impact of granulated copper slag's grinding and modification.

SimaPro 9.0 (PRé Sustainability) software was utilized to carry out the analysis, and the LCA calculations were completed using the CML-IA baseline methodology. Abiotic resource depletion is expressed as "Abiotic Depletion Factor or Potential, ADF/ADP", Climate Change is expressed as "Global Warming Potential, GWP", Human Toxicity expressed as "Human Toxicity Potentials, HTP", Acidification is expressed as "Acidification Potential, AP", Eutrophication/Nutritification expressed as "Nutritification Potential, NP or EP", and Photo-oxidant Formation is expressed as "Photochemical Ozone Creation Potential (POCP)" are characterization factors included in the impact categories of the selected method. Their findings showed that blended cement with MGCS had a greater impact on human toxicity (about 6.52% higher) than PC. They attributed this to the additional electricity input during the MGCS's heating and the MGCS's poor grinding during the materials milling, which led to more power depletion. PC had the greatest impact compared to the other impact

categories that were examined. Similar outcomes were found in this study as well; as previously noted, PSC performed better than PC in most of the impact categories examined.

3.3. Sensitivity Analysis (SA)

A SA was carried out as part of the life cycle assessment for the three cement types to evaluate the reliability of the results and their receptivity to changes in the parameters that were used. The approach described in the methodology chapter was used to conduct the sensitivity analysis. The associated hotspot, which is illustrated visually in Fig. 19, 20, and 21 of Appendix 1, is electricity as determined by the analysis of the LCIA results of each of the cement types. The input data for electricity as obtained in the inventory analysis was then varied for the three cement types by increasing and decreasing by 10% as seen in Table 6.

Table 6. Electricity input varied for Sensitivity Analysis

	Magnesia cement	PC	PSC
Actual electricity input	8.67	71.92	68.37
Increase of 10%	9.537	79.112	75.207
Decrease of 10%	7.803	64.728	61.533

Additional calculations were then performed in SimaPro 9.0 using the varied input of electricity, all other parameters are kept the same as in the original version according to the collected inventory data, and the impact assessment method was also IMPACT 2002+. Fig. 18 presents the normalization results of the damage categories from the sensitivity analysis, using the increase of 10% and decrease of 10% in electricity. In Appendix 2, Table 9 and 10 for the two scenarios provide further information on the normalization results of the sensitivity study as obtained from SimaPro.

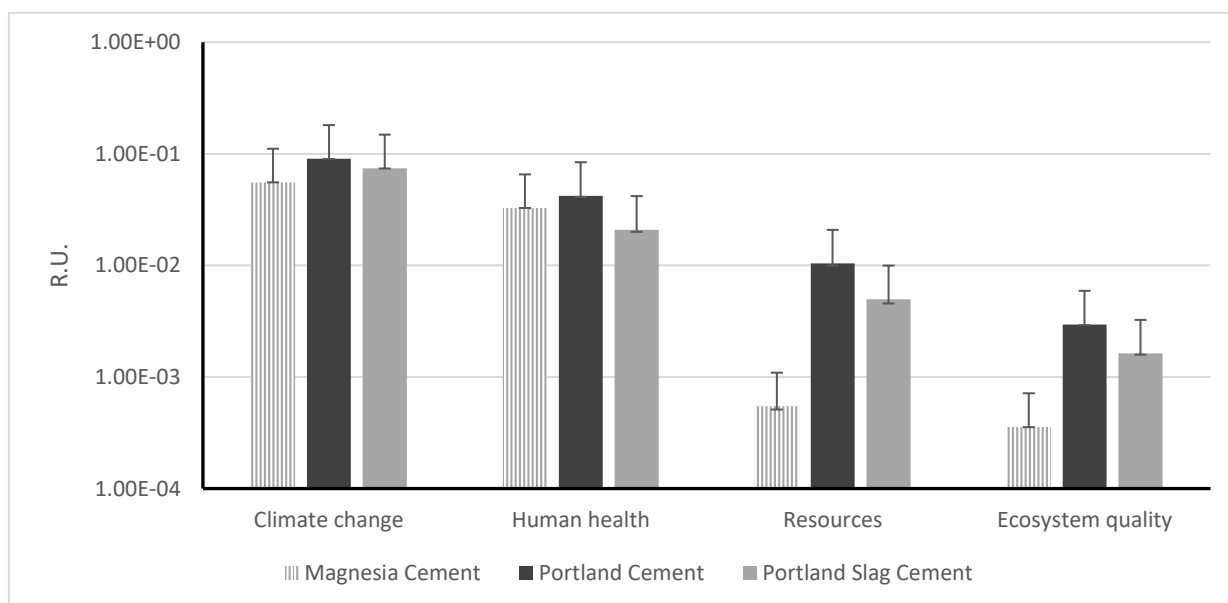


Fig. 18. LCIA normalization results for the sensitivity analysis using a 10% increase and decrease in electricity.

Fig. 18 shows that PC continues to have the biggest impact across all four categories in both instances. The graph shows that the most impacted category is climate change, whereas the least impacted one is ecosystem quality. Using the obtained values for the scenarios as indicated in Tables iii and iv of

the appendices, the results of the sensitivity study indicate that in the first scenario, involving a 10% increase in electricity, PC's climate change impact is still roughly 38.8% more than that of magnesia and 17.7% greater than that of PSC. In the human health category, the impact of PC is about 24% greater than the impact of magnesia cement and about 49.3% greater than PSC. The impact of PC in the resources category is about 94.6% greater than magnesia cement while it has about 50% more impact when compared to PSC. In the ecosystem quality category, PC's impact is about 88% greater than magnesia cement, and 49% greater than the impact of PSC. In the second scenario with a decrease of 10% in electricity, when compared to magnesia cement and PSC, PC has a greater impact of about 38.2% and 17.8% respectively in the climate change category. In the human health category, the impact of PC is about 20.4% bigger than that of magnesia cement and about 51% bigger than the impact of PSC. In the resources category, PC has an impact of about 94% more than magnesia cement and about 54% more than PSC. In the ecosystem category, the impact of PC is still about 88% more than magnesia cement and 45.7% greater when compared to PSC.

According to the SA results, each cement type still performs better in both scenarios in the ecosystem and resources categories than in the climate change and human health categories. In all cases, magnesia cement continues to make the smallest contribution to all four categories. According to the SA results, the input values for electricity gathered in the inventory data and utilized in the LCA model of the impact assessment had no significant influence on the outcomes of the LCA.

Conclusions

1. After conducting a literature review, it has been determined that approximately 7% of global carbon dioxide emissions originate from manufacturing Portland cement, primarily due to the production of clinker. To address this issue, researchers are exploring magnesia cement as a potential alternative. However, the economic separation of the required raw materials has been a major challenge. Recent technological developments provide hope for overcoming these barriers, and the Abo Akademi mineral carbonation process in Finland is being piloted using MgO from serpentinites. It was also determined that it was necessary to assess the environmental benefits of producing magnesia cement.
2. Inventory data on the production inputs and outputs of the cement types were collected from scientific literature and the Ecoinvent database. Electricity was identified as the input with the largest quantity across all cement types, and CO₂ emissions were the highest among the emissions produced. The environmental benefits of producing magnesia cement were determined using a life cycle assessment approach, and a comparative assessment was performed to evaluate its impact and compare it to that of Portland cement and Portland slag cement.
3. The life cycle impact assessment results were obtained following simulation in SimaPro 9.0 software, from the analysis of each cement type, the main hotspot was identified as electricity. The characterization results of the comparative analysis showed that magnesia cement had the least impact in most of the impact categories, while Portland cement had the greatest impact in the majority of the impact categories with impact reaching up to 97% greater than magnesia and Portland slag cement depending on the category. In the aquatic acidification and mineral extraction categories, magnesia cement and Portland slag cement had the biggest impacts respectively. The impact of magnesia cement in the aquatic acidification category is about 44% greater than the impact of Portland cement and about 78% greater than the impact of Portland slag cement. The normalization results showed the impacts of each type of cement in four different damage categories, with the impact of all three cement types being greatest in the climate change category and the least in the ecosystem quality category. However, Portland cement had the most impact while Magnesia cement had the smallest impact across all categories except for human health. In the climate change category, Portland cement has an impact that is about 38.6% more than that of magnesia cement and around 17.8% greater than that of Portland slag cement.
4. The sensitivity analysis results also demonstrated that Portland cement remained the biggest contributor, with magnesia cement having the least impact across all damage categories. It also demonstrated that the production of all three types of cement has the most impact on the category of climate change. Based on these results, it may be concluded that the life cycle impact assessment model and calculations produced reliable results.
5. In comparison with the other cement types that were taken into consideration in this study, the overall results of the life cycle assessment show that magnesia cement performed better in most of the impact categories analyzed. The study highlights the Abo Akademi process as a potentially sustainable and cost-effective source of magnesite, demonstrating advantages in the climate change category due to its relatively low carbon footprint. Future research should include a detailed assessment of the commercial feasibility and scalability of producing magnesia cement using the Abo Akademi process, taking into account economic viability, market demand, and any potential difficulties or limitations towards widespread adoption. Further research could also focus on comparing the chemical and mechanical properties of magnesia cement to other cement types.

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Appendices

Appendix 1. Supplementary Figures of LCIA Results

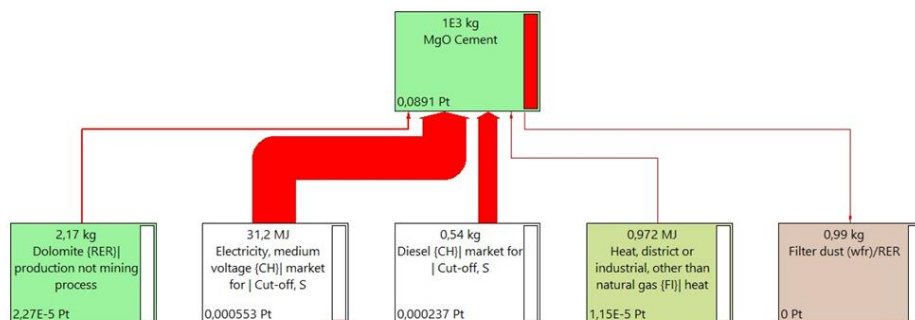


Fig. 19. Network flow chart for Magnesia cement

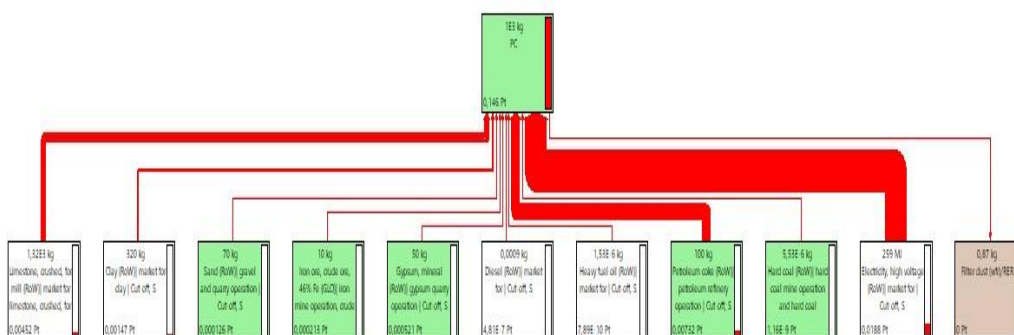


Fig. 20. Network flow chart for PC

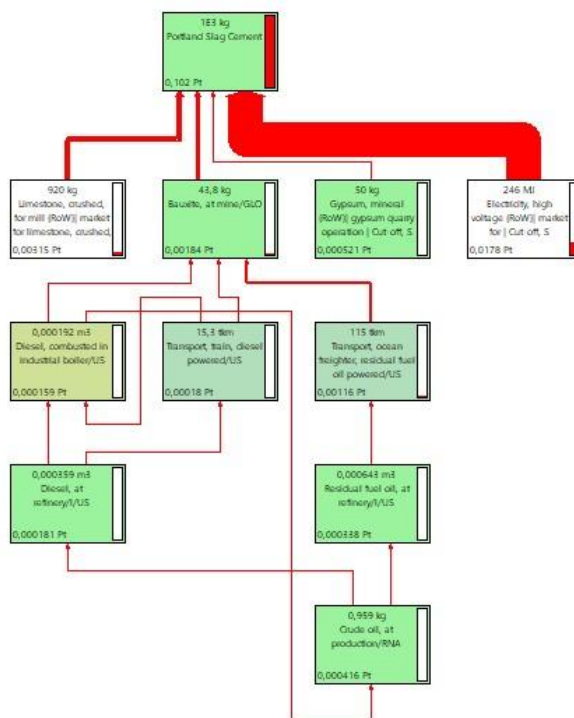


Fig. 21. Network flow chart for PSC

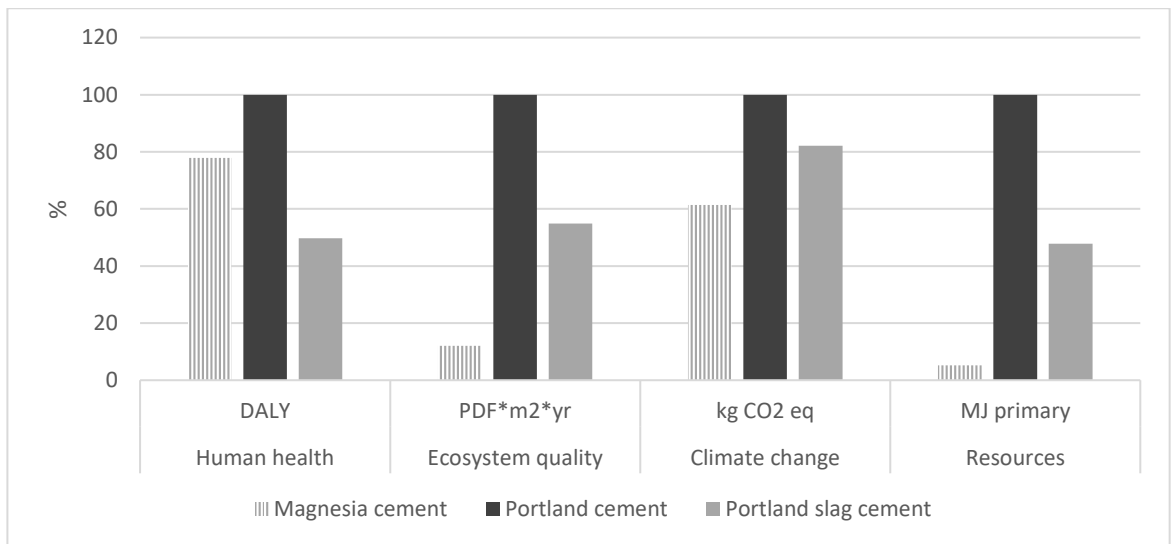


Fig. 22. LCIA damage assessment results for the comparative analysis of Magnesia, Portland and PSC.

Appendix 2. Supplementary Tables of LCIA Results

Table 7. Damage assessment results for the comparative analysis of Magnesia, Portland and PSC

Damage Category	Unit	Magnesia cement	PC	PSC
Human health	DALY	0.000231754	0.000297836	0.000148008
Ecosystem quality	PDF*m2*yr	4.890431397	40.51985139	22.23620479
Climate change	Kg CO ₂ eq	549.354857	894.2827965	734.8449176
Resources	MJ primary	83.0261214	1581.135804	756.5715007

Table 8. Characterization results for the comparative analysis of Magnesia, Portland and PSC

Impact Category	Unit	Magnesia cement	PC	PSC
Carcinogens	kg C2H3Cl eq	0.007611767	0.545183014	0.31053239
Non-carcinogens	kg C2H3Cl eq	0.015957307	0.488870387	0.438630605
Respiratory inorganics	kg PM2.5 eq	0.330887944	0.420905147	0.208179814
Ionization radiation	Bq C-14 eq	307.3328437	1167.180309	759.8091664
Ozone layer depletion	kg CFC-11 eq	7.07471E-07	1.23802E-05	2.1356E-06
Respiratory organics	kg C2H4 eq	0.000441556	0.022801373	0.010582528
Aquatic ecotoxicity	kg TEG water	219.9965365	13106.82964	9460.194993
Terrestrial ecotoxicity	kg TEG soil	45.2331996	3326.082703	2020.322325
Terrestrial acid/nutri	kg SO ₂ eq	4.328454988	12.22220286	5.131089648
Land occupation	m ² org.arable	0.018348417	0.772003104	0.407541463
Aquatic acidification	kg SO ₂ eq	4.22756907	2.361167814	0.937139674
Aquatic eutrophication	kg PO ₄ P-lim	0.00051044	0.01882853	0.012572988
Global warming	kg CO ₂ eq	549.354857	894.2827965	734.8449177
Non-renewable energy	MJ primary	82.99303972	1579.602574	734.3862757
Mineral extraction	MJ surplus	0.033081678	1.533229278	22.18522731

Table 9. Normalized results for the sensitivity analysis using a 10% increase in electricity of Magnesia, Portland and PSC

Damage Category	Unit	Magnesia cement	PC	PSC
Human health		0.032686924	0.042929777	0.021757913
Ecosystem quality		0.000359113	0.00300084	0.001664017
Climate change		0.0554926	0.090774552	0.074649016
Resources		0.000582138	0.01085127	0.005403553

Table 10. Normalized results for the sensitivity analysis using a 10% decrease in electricity of Magnesia, Portland and PSC

Damage Category	Unit	Magnesia cement	PC	PSC
Human health		0.032667642	0.04105987	0.019980306
Ecosystem quality		0.00035489	0.002915058	0.001582469
Climate change		0.055477081	0.089870573	0.073789657
Resources		0.000510486	0.009956477	0.004552928