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Review

Unlocking Alternative Cement Solutions: Utilizing Wastes and By-Products for Magnesium Phosphate Cement Development

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Abstract

Concrete is the most used material worldwide, with cement as its essential component. Cement production, however, has a considerable environmental footprint contributing nearly 8% of global CO_2 emissions, largely from clinker calcination. This review aims to examine strategies for reducing these emissions, with a particular focus on alternative materials for producing magnesium phosphate cements (MPCs). Specifically, the objectives are first to summarize mitigation pathways, such as CO_2 capture, energy efficiency, and alternative raw materials, and second evaluate the feasibility of using industrial wastes and by-products, including low-grade MgO, tundish deskulling waste (TUN), boron-MgO (B-MgO), and magnesia refractory brick waste (MRB), as MgO sources for MPC. The review highlights that these materials represent a promising route to reduce the environmental impact of cement production and support the transition toward carbon neutrality by 2050.

Keywords: cement; alternative cement; magnesium phosphate cements; circular economy; sustainability

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1. Current Situation

1.1. Environmental Issues

The future of the planet under ongoing environmental change remains uncertain, yet it is clear that urgent action is required to reverse current trends. Humanity carries the responsibility to safeguard the environment, public health, and the well-being of future generations by striving for zero pollution and a sustainable economy. Achieving this requires adherence to fundamental principles such as equity and sustainability, with climate action representing one of the most pressing challenges of our time. Coordinated global efforts and the development of robust international environmental frameworks are therefore essential to drive meaningful change by 2050.

At the policy level, the European Union (EU) and many other countries have committed to ambitious environmental targets aligned with international agreements. Achieving consistency across national and global strategies is critical, as illustrated by the United Nations Sustainable Development Goals (SDGs), which provide a comprehensive framework for advancing sustainability worldwide.

The growing world population and materials consumption are causing negative impacts on the planet. In 2022 (latest figures available), the total waste generated in the EU was around 2.233 Mt [1]. Preventing waste is a part of the EU's strategy to achieve efficiency of the resources and a circular economy. The amount of waste generation depends on the development of society, although it is important to create solutions to ensure that waste is treated properly. The Waste Framework Directive (Directive 2028/851) defines some basic waste management principles, where waste prevention is the preferred option and the worst option is landfill. The package of measures on waste will lead to the creation of a circular economy and allow the deficiencies of the waste sector to be corrected. By using these wastes as raw materials, humans are dealing with another global problem: the scarcity of resources to produce materials.

The Directive 2018/850 on the landfill of waste specifies that all member states will implement strategies to ensure that the recycled or recovered waste does not end up in landfills by 2030. The main goal is to reduce the negative landfill effects on the environment and human health and set out minimum responsibility requirements for all producers. In addition, the member states have agreed that waste must receive adequate treatment before being deposited in landfills. Waste landfills are divided into three categories: hazardous, non-hazardous, and inert.

Carbon dioxide (CO_2) stands as a significant constituent among the greenhouse gases (GHGs) contributing to the global warming phenomenon. The escalation in human activities steadily amplifies the emission levels of these GHGs year by year. In 2023, global carbon dioxide emissions resulting from energy combustion and industrial processes recorded a notable increase by 1.1%, culminating in a total of 37.4 Gt [2]. By 2050, the world's population will have increased to 9 billion [3]. In the context of the climate emergency and achieving the 2030 goals focusing on GHG emissions reduction and carbon neutrality by 2050, the Directive 2010/75 on industrial emissions is the main instrument for controlling and/or preventing pollutant emissions from industries to the atmosphere, water, and ground. This directive is based on the integrated approach, the use of the best available techniques, and several inspections, among others.

The production and use of energy are the principal cause of GHG emissions, along with transport. Final energy consumption in the EU for 2022 decreased by 3.9% compared to 2021 (latest figures available), reaching a total of around 37,771 PJ [4]. Of this total, the three sectors that consumed the most energy were transport, households, and industry [4]. According to the International Energy Agency (IEA), industrialized economies achieved a record decline in carbon dioxide emissions by 2023, despite gross domestic product (GDP) growth, as a result of low-emission energy generation [5]. The EU has different climate rules to ensure that GHG emissions' reduction would be at least 40% in 2030 compared to 1990. In particular, the Directive 2018/844 intends to achieve: (i) energy consumption reduction and (ii) an increase in the proportion of renewable energy consumed. The EU is trying to develop a decarbonized, efficient, secure, and sustainable energy system by 2050.

1.2. Cement Sector

Cement stands as one of the pivotal materials significantly contributing to the social and economic development of society. World cement production has increased in recent decades, and in 2023, the estimated global production was 4.1 Gt [6]. Cement is the fundamental component in developing concrete and acts as a binder for the concrete particles, giving cohesion and mechanical resistance through chemical and physical processes. The construction sector uses concrete, which is the most consumed material on Earth [7]. The cement sector is one of the most challenging industries, as it has multiple regulatory frameworks in Europe to achieve carbon neutrality by 2050. The transition is accompanied by new regulations, technologies, and infrastructures.

Cembureau, the European Cement Association, proposes a 40% reduction in gross carbon dioxide emissions down the value chain by 2030 compared to the 1990 carbon dioxide emissions (783 kg $CO_2 \cdot t^{-1}$ of cement), as an intermediate step towards carbon neutrality by 2050 [8]. Some Cembureau targets to achieve climate neutrality by 2050 are based on reducing clinker and deploying innovative technologies, shown in Figure 1. This challenge can be addressed through renewable energy and efficiency improvements. Additional strategies include the adoption of clinker substitutes, the use of supplementary cementitious materials (SCMs), and the incorporation of sustainable alternatives, such as waste or by-products.

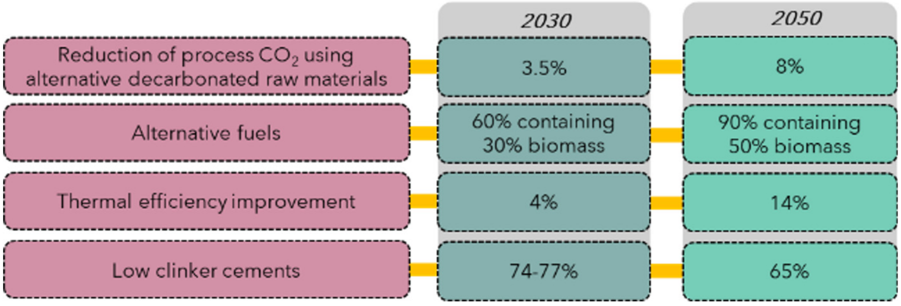

Figure 1. Cembureau targets to climate neutrality by 2020 (adapted from [8]).

1.2.1. Ordinary Portland Cement Industry

Cement production depends on the geographical area, the availability of raw materials, and the technologies used, among other aspects. Cement production was 1.4 Gt in 1995 and 4.1 Gt in 2023 globally, a good indicator to show the growth trend of the construction industry [6]. Cement is related to fast-growing economies. China was the highest contributor to world production, with 55% of the total of 4158 Mt in 2022 [9]. China produces over half of the world's cement, followed by India with 8% [10]. Hence, the forecast for the next few years is that other developing countries in Africa and Asia will have an increase in the demand for cement. The new international policies enhance international coordination and collaboration for the decarbonization roadmap of the cement industry.

Cement manufacturing is highly energy intensive. Ordinary Portland cement (OPC), widely used in civil engineering and construction since the 19th century, is valued for its abundant raw materials, low cost, and reliable performance. It is produced mainly from calcined limestone and aluminosilicates (usually clay) [11]. OPC is a hydraulic binder that, mixed with water, forms a paste that sets, hardens, and preserves its resistance and stability. OPC is obtained by mixing clinker, gypsum (calcium sulfate), and other additives. The clinker is the main component, which is subjected to a series of steps before it is mixed with the other components. This process encompasses the extraction of raw materials, followed by crushing, grinding, calcination, and subsequent cooling and grinding [7]. Its composition is shown in Table 1, and its mineral phase composition is shown in Table 2. The percentage of gypsum depends on the type of cement and serves to retard its setting time.

Table 1. Clinker elemental chemical composition [12].

Oxide	Name	Wt.%
CaO	Lime	60–70
SiO_2	Silica	18–22
Al_2O_3	Alumina	4–6
Fe_2O_3	Iron oxide	2–4

Figure 2 shows the manufacturing process flows, the energy and heat demand (inputs), and emissions associated with each stage. Cement manufacture requires large amounts of raw materials and involves high amounts of energy and carbon dioxide emissions, as depicted with icons in Figure 2. Specifically, the production of a ton of clinker requires approximately 1.5 tons of raw materials. Consequently, cement manufacture entails a high consumption of natural resources [13].

Table 2. Clinker mineral phase composition [12].

Oxide Composition	Common Name	Cement Notation	Wt.%
$3CaO{\cdot}SiO_2$	Alite	C_3S	50–65
$2CaO{\cdot}SiO_2$	Belite	C_2S	15–25
$3CaO{\cdot}Al_2O_3$	Tricalcium aluminate	C_2A	5–15
$4CaO{\cdot}Al_2O_3{\cdot}Fe_2O_3$	Calcium alumina-ferrite	C_4AF	5–12

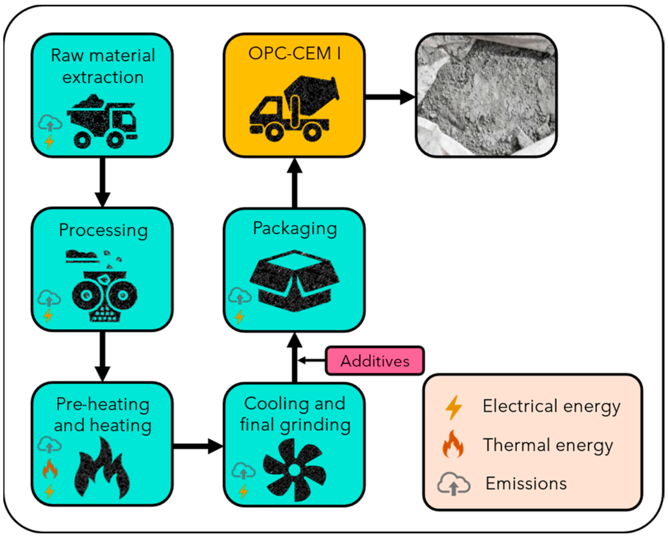

Figure 2. Process flow diagram for the manufacturing process of OPC.

The manufacturing process is energy intensive due to the consumption of high quantities of fuels (mainly from non-renewable sources of thermal processes). Coal is the principal energy carrier with 70% of total energy consumption, followed by oil and natural gas with 24% and alternative fuels and biomass with just over 5% [14]. Around 3% of the global primary energy is consumed by the cement sector [15]. The global thermal energy intensity of clinker from 2020 to 2023 was 3.5–3.6 $GJ{\cdot}t^{-1}$ per year [10,16]. In the net-zero emissions by 2050 scenarios, the anticipated thermal energy intensity for clinker production is projected for 2030 to be 3.3 $GJ{\cdot}t^{-1}$ per year [10,13]. The predominant source of energy is in the form of fuel, primarily derived from fossil fuels for clinker production, alongside electricity consumption [9,10]. In cement manufacturing, the heating process consumes 70–80% of the total energy consumption and 20–30% of electricity [14].

The manufacturing process of cement emits contaminant gases into the atmosphere (CO_2, NO_X, SO_2, and other pollutants) coming from the burning of fuels in the kiln and fine particles dragged by the exhaust gases of the kiln [15]. The cement industry contributes approximately 5–7% of the total global anthropogenic carbon dioxide emissions and 8% of the global emissions [3,17,18]. Specifically, the direct carbon dioxide intensity of cement production increased by about 1.5% per year from 2015–2023 [10]. Seventy to eighty percent of carbon dioxide emissions come from the involved chemical reaction to obtain CaO, and the rest of the emissions come from the energy required to reach a high temperature in the rotary kiln during calcination, among other processes such as transport and grinding [3,8].

1.2.2. Alternative Cements

The advancement of alternative cements has allowed reducing the clinker content. Replacing part of the clinker with other materials can improve both the properties and the environmental impact.

Building materials involve several environmental impacts during their life (manufacturing, construction, use, maintenance, and final disposal/demolition phase). Several strategies are available to reduce the environmental impact of cement production. Key actions include improving energy and material efficiency, adopting low-carbon technologies, using alternative fuels, and incorporating substitute materials. The key actions to reduce the impact are [19]:

- Reduction of clinker by using alternative decarbonized mineral additives.
- Alternative fuel usage, promoting the circular economy and using renewable energies to replace fossil fuels.
- Optimization of energy and technology efficiency.
- Carbon capture and storage (CCS) and carbon capture and use (CCU) to transit to a net-zero model.

This research focuses on alternative cements that can reduce OPC consumption. Sustainable cements, with lower environmental impacts, offer a pathway toward low-carbon manufacturing in the cement sector. A selection of publications related to alternative cementitious materials was made in 2024 by using the Web of Science (WoS) webpage, considering journals and books, with a total of 1720 publications. As depicted in Figure 3, the quantity of publications and citations pertaining to the advancement of this research field has been steadily increasing over the years. Of the total amount of these publications, a detailed analysis was conducted to ascertain the percentage of the contribution of each country to the total number of publications from the previous results obtained from the WoS, as illustrated in Figure 4. As evidenced in the map chart, the country with the highest number of publications on the development of alternative cementitious materials is the USA, followed by China and India.

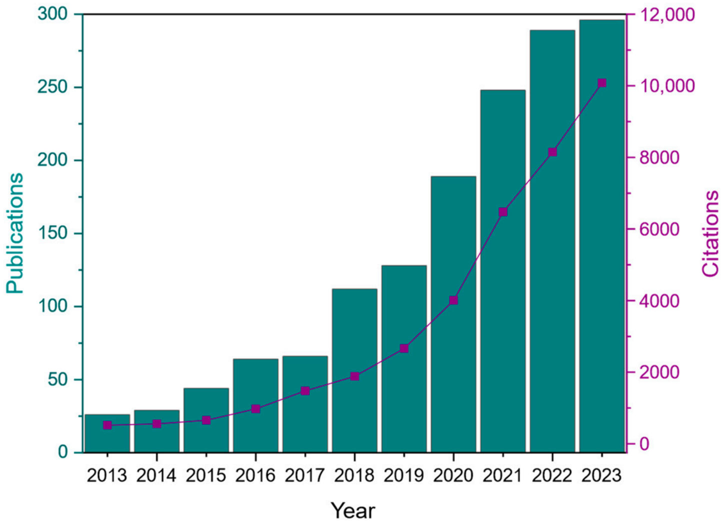

Figure 3. Number of publications and citations on alternative cementitious materials.

The strategy to search for sustainable alternatives to OPC can reshape the cement industry into a pivotal sector driving the circular economy. It involves the development of sustainable materials made from by-products or waste, presenting opportunities for economic viability. Some examples of alternative binders are:

- Limestone-calcined clay cement (LC3). LC3 is a relatively new cement based on SCMs. Specifically, LC3-50 is obtained by mixing clinker (50 wt.%), calcined clay (30 wt.%), limestone (15 wt.%), and gypsum (5 wt.%). This binder has a high potential to reduce carbon dioxide emissions due to the reduced clinker content, replaced by calcined clays and limestone [20–22].
- Alkali-activated cement (AAC). AAC is produced like cement, but its properties are like those of sintered ceramic. AAC is produced by the reaction of amorphous aluminosilicates with alkali. The subsequent requirement is for reactive solid aluminosilicates and an alkaline activating solution. The source materials of aluminosilicate are frequently industrial waste or by-products like municipal solid waste (MSW), blast furnace slag (BFS), and fly ash (FA), among others. Some of the technical issues associated with these cements are their hardening rates, as well as high shrinkage. AAC is generally used as precast material [15,17–19].
- Calcium aluminate cement (CAC) and calcium sulfoaluminate cement (CSAC). CAC is based on aluminate. On the one hand, the major component in CAC is calcium [23,24]. This type of cement exhibits both early strength and high-temperature resistance. Their applications are specifically geared towards scenarios where resistance to elevated temperatures is crucial [23,24]. The main phase of CSAC is ye'elimite ($C_4A_3\overline{S}$). Other secondary phases are belite (C_2S), calcium sulfate, and gehlenite (C_2AS). A diminished proportion of calcium and lower calcination temperature contribute to a notable reduction in the environmental footprint. Short setting time, high early strength, permeability, and corrosion resistance, among others, are some of the CSAC properties. Then, CSAC can be applied in the solidification and stabilization of hazardous materials [23,24].
- Belite cement (BC). BC is primarily composed of belite, C_2S (40–50%), alongside alite (C_3S) and calcium aluminates. The impact on the environment is reduced by their lower clinker content. BC exhibits slower hydration rates, resulting in lower early-age compressive strength. This is widely applied in hydraulic concrete to control temperature cracking and reduce thermal stresses and cracking [25–27].
- Magnesium phosphate cement (MPC). MPC belongs to the chemically bonded ceramic (CBC) family, more specifically classified as chemically bonded phosphate cement (CBPC). MPC is obtained by mixing a magnesium source with phosphate salt. CBC has remarkable properties: fast setting and good encapsulation of heavy metals and radioactive waste, due to its ability to form stable and durable matrices that effectively immobilize and encapsulate hazardous materials. MPC also can be applied as repair cement [28–30].

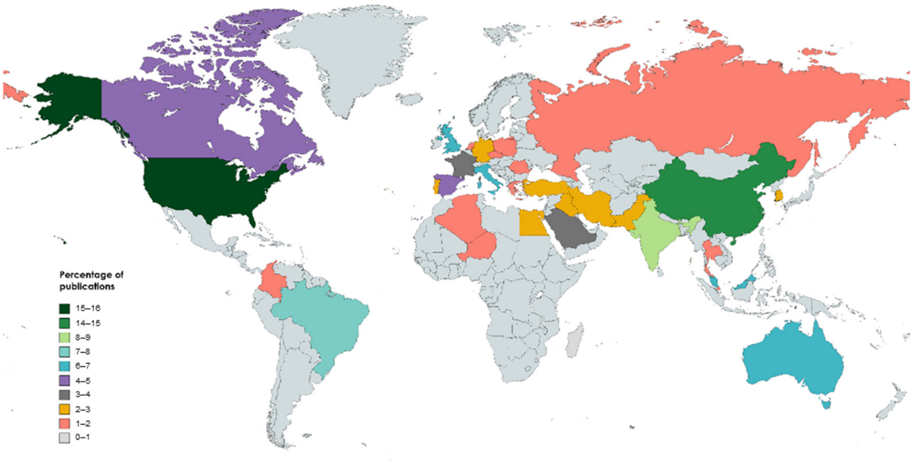

Figure 4. Percentage of publications on alternative cementitious materials with respect to country.

2. Chemically Bonded Ceramic (CBC)

CBCs encompass a category of inorganic materials exhibiting properties of both cements and ceramics, formed by chemical reactions at low temperatures (Figure 5) [31]. The structure and properties of CBC closely resemble those of ceramics; nonetheless, their formation at room temperature exhibits similarities to cementitious materials [32].

CBC is formed though the reaction between an acid and a base. As a result, acid–base cement (ABC) belongs to the category of CBC [13,32]. Specifically, the bonding of CBC is a mixture of ionic and covalent bonding, as van der Waals bonding [31,33]. The predominant types of bonding determine the properties exhibited by ceramics [31].

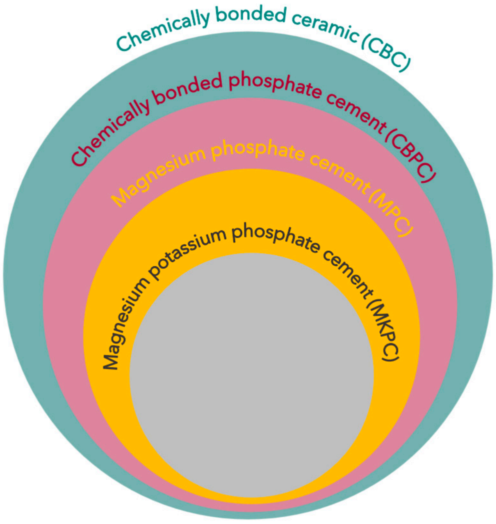

Figure 5. Classification of CBC families related to phosphate-based materials.

Research on CBC is relatively recent but essential due to its environmental advantages, such as lower GHG emissions and reduced energy demand. CBC is also cost-effective, eliminates high-temperature processing, and has applications ranging from biomedical uses to nuclear waste encapsulation and composites materials [34].

CBC is produced through a series of sequential steps, including the dissolution of a base salt in an acid medium, followed by gelation and precipitate formation, and culminating in crystallization, as illustrated in Figure 6. The resulting paste achieves a neutral pH because of the neutralization between the acid and alkali components.

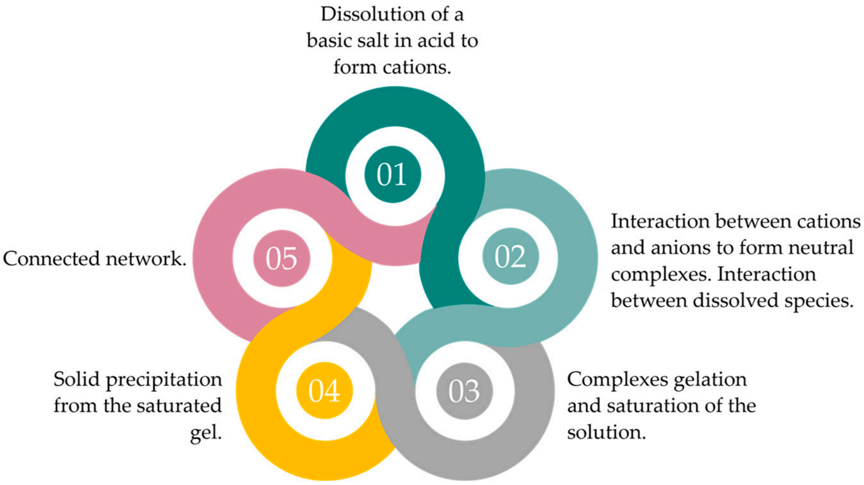

Figure 6. CBC's reaction.

The dissolution of the basic precursor is an important control factor to verify a coherent structure and a solid product [32]. In essence, if the basic precursor dissolves at a slow rate, the formation of the reaction product will correspondingly proceed slowly. As a result, the saturation of the gel will require a longer period. In contrast, if the basic precursor dissolves rapidly, precipitates will form, compromising the coherence of the structure. Therefore, the solubility of the basic precursor is a relevant factor as it directly affects the formation of the ceramic. In the context of ABC, the dissolution of the basic precursor into an acid solution is invariably partial.

As mentioned before, when phosphates are employed in the formation of CBC, this cement is referred to as CBPC. Notably, CBPC is recognized as viable as an alternative cement to conventional hydraulic cement [35,36].

2.1. Chemically Bonded Phosphate Ceramic (CBPC)

As mentioned earlier, CBPCs are derived from an acid–base reaction and demonstrate notable characteristics such as high strength and low solubility. The acid–base reaction is between a phosphoric acid and metal oxide [31]. This reaction allows combination of phosphate anions with metal oxide cations to form a phosphate gel that crystallizes as insoluble phosphates [36,37]. Equation (1) shows the reaction between the metal oxide and phosphoric acid. In this equation, the letter x refers to the valence of the metal M/n, and the letter m refers to an arbitrary value that defines the amount of water added to the reaction.

$$MO_{\frac{x}{2}} + nH_3PO_4 + mH_2O \rightarrow MH_{3n-x}(PO_4)_n + \left(m + \frac{x}{2}\right)H_2O \tag{1}$$

The final properties of the cement will depend on the solubility of the raw material and its pH level. CBPC can be formulated from different raw materials. There are several possible sources of phosphate [38,39]. Initially phosphoric acid was used, but due to its difficult handling (corrosive liquid) and the rapid setting that occurs, it has fallen into disuse. Later, the use of ammonium phosphate salts gained prominence, but when forming the cement, ammonia gas is released, which is a toxic gas, so it has also been losing prominence [40]. Finally, potassium phosphate salts have been the phosphate source that shown advantage over others, even though there are other interesting phosphate salts, such as sodium, aluminum, etc. [39].

One of the frequently employed options is monopotassium phosphate (MKP, KH_2PO_4), among other potassium phosphate salts [41,42]. Concerning oxides, they must exhibit an appropriate solubility (i.e., low solubility) for facilitating the formation of CBPC, because the formation of the cement depends on the dissolution kinetics of the oxide used [40]. The reduced solubility contributes to a delayed setting time, which in turn enhances the workability of the cement [37]. If the oxides exhibit excessive solubility, they will precipitate in crystalline form, impeding the formation of a three-dimensional network. Conversely, if the solubility is too low, an insufficient supply of ions hinders the rearrangement into a three-dimensional network [31]. The main oxides used are magnesium oxide (MgO), calcium oxide (CaO), and zinc oxide (ZnO).

When mixing a phosphoric acid and a metal oxide in an aqueous solution, the formation of CBPC occurs in three stages [43,44]:

1. Dissolution of the phosphoric acid in water, phosphate releases anions and forms an anion phosphate solution of low pH.
2. Low pH increases the solubility of the alkaline component, and a gradual dissolution occurs in the solvent at the same time, which releases cations in the acidic solution.
3. The reaction to obtain precipitation of a crystalline salt, also named neutral phosphate, is between the phosphate anions and the alkaline cations.

Whether the result is a well-ordered ceramic or a crystalline precipitate depends directly on the rate of dissolution of the oxides in the acid solution and on the rate of the exothermic acid–base reaction. To obtain a well-crystallized ceramic, the following specific requirements are needed [32]:

- The solubility of the oxides should be sufficiently high to facilitate the formation of a saturated gel, yet not excessively high to allow for gradual crystallization of the gel.
- The rate of the exothermic acid–base reaction should be slow enough to enable the gradual and steady crystallization of the phosphate gel.

CBPC has extensive advantages such as rapid hardening, high early strength, and high-temperature resistance. CBPC's strength is due to the strong covalent bonds resulting from the acid–base reaction, contrasting with the weaker bonds resulting from the hydration process in conventional cement. Initially, CBPC was used in biomedical applications, specifically in the dental sector. At the moment, CBPC has found diverse applications, including repair and reinforcement cement in civil engineering, encapsulation and solidification of radioactive waste, and in biomedical uses [36,45,46]. The essence of ABC lies in its ability to use acid and alkaline waste or by-products as raw materials. Producing ceramics through these chemical processes demands less energy compared to conventional ceramics production. For these reasons, CBPC can contribute to diminishing environmental impact and promoting a circular economy.

2.2. Magnesium Phosphate Cement (MPC)

One of the most extensively studied cements among the CBPCs is MPC. MPC is obtained from the exothermic acid–base reaction between a magnesium source (typically as an oxide) and a phosphate source. MPC obtained from MKP as a phosphate source stands out, and in the current scenario, in this case it is called and known as magnesium potassium phosphate cement, using in this case the acronym MKPC instead of MPC to differentiate it from the rest. Thus, the term MPC refers to the generic term, while the term MKPC refers to the case of using MKP as a phosphate source (Figure 5).

Magnesium oxide (MgO) is the most common and widely used raw material for MPC due to its moderate solubility in an acid–phosphate solution compared to iron and calcium oxides [43]. To achieve this solubility, MgO undergoes calcination at temperatures above 1000 °C. Elevated temperatures reduce the porosity and permeability of MgO, leading to an increase in particle size. The diminished solubility of the calcined magnesium oxide powder can be attributed to a notable decrease in its surface area. A less reactive form of MgO contributes to the development of a more compact microstructure in MPC, as well as extends the setting time, leading to an improvement of the mixing process [37].

MPC is usually synthesized by an acid–base neutralization reaction, involving calcined magnesia powder and a phosphate source, at room temperature and in aqueous media, shown in Equations (2) and (3), where the two most used sources of phosphate are shown. The former, MKP, is commonly used as a fertilizer or food additive [28,47,48]. The latter, monoammonium phosphate (MAP), as mentioned above, has fallen into disuse due to the potential release of ammonia gas [30].

$$MgO(s) + KH_2PO_4(s) + 5H_2O(l) \rightarrow MgKPO_4{\cdot}6H_2O(s) \quad (2)$$

$$MgO(s) + NH_4H_2PO_4(s) + 5H_2O(l) \rightarrow MgNH_4PO_4{\cdot}6H_2O(s) \quad (3)$$

The final product of the first reaction is a magnesium–potassium phosphate binder, MKPC, and the crystal is named K-struvite ($MgKPO_4{\cdot}6H_2O$) [49]. The final product of the second reaction is struvite, which is a magnesium ammonium phosphate hexahydrate ($NH_4MgPO_4{\cdot}6H_2O$). The distinction between K-struvite and struvite lies in the presence of potassium. Specifically, in K-struvite, potassium replaces ammonium in the chemical composition, as shown in Figure 7. Both K-struvite and struvite have an orthorhombic structure. They have important cementitious properties and are widely used in the MPC field. In fact, K-struvite is preferred due to its reduced release of ammonia gas during setting, lower setting characteristics, and lower exothermicity. These properties enhance the ease of handling and workability of pastes while ensuring proper and controlled setting [50,51].

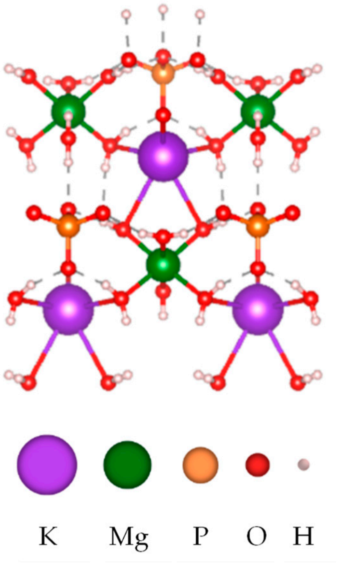

Figure 7. K-struvite crystal phase (adapted from [52,53]).

The formation of K-struvite takes place in three steps [31,32,40,44]:

- The interaction between MgO and an acid phosphate solution results in the creation of positive colloidal solutions. In this process, the cations of the dissolved species are surrounded by water molecules, generating positively charged aqueous sols through hydrolysis.
- Through an acid–base reaction and gel formation by condensation, positive aqueous sols engage with phosphate anions, leading to the formation of hydrophosphate gel or binder phosphate salts.
- The gel undergoes a transformation into ceramic material as it becomes saturated, and gel crystallizes around the unreacted metallic oxide granules. This crystalline network forms a monolithic ceramic structure.

MPC was developed in 1940 by Prosen as ceramic materials for the molds used in lost casting [54]. Nowadays, MPC has captured increasing attention for its applications, such as bone substitution, stabilization, and solidification of waste and composite cement with fibers [50,55]. MPC (and MKPC) is distinguished by several key characteristics, including near neutral final pH, low drying shrinkage, minimal water demand, and high early-age mechanical strength compared to other cements [49]. Additionally, different variables directly affect the final properties of MPC, likewise the ratio between the acid and basic components, the ratio between liquid and solid (L/S), and the reactivity of MgO [39,40,56].

MPC exhibits highly exothermic setting reactions [32,54,57]. The phosphate source must possess adequate solubility to allow controlled setting at a moderate speed, allowing the material to dissipate heat gradually during the setting process and thereby preventing thermal shock. The preferred candidate is MKP (KH_2PO_4) [39,40]. In recent years, the scientific community has sought to reduce the production costs of MPC by using secondary sources of magnesium and introducing mineral and industrial waste. Despite this, the high cost of this type of cement is still a factor to be considered when compared to conventional cement, such as OPC [39,40]. Thus, for the coming years and for the sustainable development of MPC, it would be interesting to find phosphate sources coming from secondary sources.

Magnesium oxide can be derived from primary or secondary sources. In the case of primary sources, it involves the calcination of pure MgO from magnesite or dolomite minerals to obtain dead burned magnesia (DBM) [58]. In the case of secondary sources, MgO sources come from waste and industrial by-products rich in this compound, such as low-grade magnesium oxide (LG-MgO), tundish deskulling waste (TUN), boron–magnesium oxide (B-MgO), or magnesia refractory brick waste (MRB). Using by-products and waste promotes future sustainable construction practices, advancing the principles of a circular economy environment preservation.

2.3. Significance of MPC

Research in the field of MPC has expanded significantly in recent years. MPC could play a substantial role in reducing the use of OPC due to the advantages. In recent years, numerous studies have been undertaken to investigate the properties and applications of MPC.

A literature search was conducted to identify the most relevant data and advancements in the research area of MPC within the construction and building industry. This study allows us to analyze the characteristics of this field over the past decade. The main goal of this literature search is to evaluate and comprehend the progress made in this field, with a focus on its significance in the construction sector. Additionally, it aims to spotlight the most impactful publications, identify the authors with significant contributions, and highlight the regions that have been most active in this area. The data source used was WoS, considering the metadata features and the publications [59]. A total of 628 publications in significant journals and books related to MPC publications were selected from 2013 to 2024. A meticulous selection process was carried out to identify publications aligning with the research area, while excluding those that did not meet the criteria. The unifying factor among these documents was the presence of the term "MPC", and the required application was specifically centered on the construction sector. The results revealed a clear trend of escalating publications year by year, reaching its peak volume in 2022. Accordingly, the trend in evolution indicates a likely continuation of increasing publications in the forthcoming years. Hence, the maximum number of publications was in 2022, with 112 publications, as shown in Figure 8.

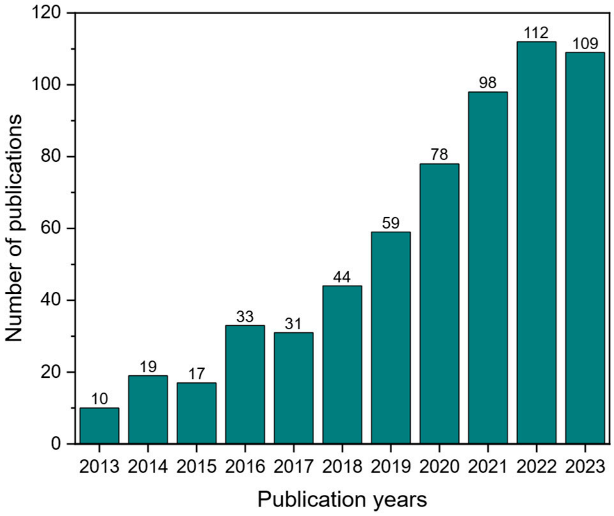

Figure 8. Evolution of publications over the years.

The trend in MPC research is fully associated with environmental regulations related to the reduction of the environmental impacts of the cement industry. Consequently, it also reflects the development and use of alternative cements [18].

The three most common WoS categories are "Materials Science Multidisciplinary", "Construction Building Technology", and "Engineering Civil". The top journals in the research areas are related to "Materials Science", "Engineering", and "Construction Building Technology". "Materials Science" stands out as the most common research area, contributing to 69.9% of the total publications in this field. The most common publisher is Elsevier, followed by MDPI.

The top five recurrent publication journals are "*Construction and Building Materials*" (28.7%), "*Materials*" (6.1%), "*Journal of Building Engineering*" (5.6%), "*Cement and Concrete Research*" (4.1%), and "*Journal of Materials in Civil Engineering*" (3.8%). Articles make up 91.9% of the total percentage, while the remaining percentage consists of review articles and early-access publications.

Table 3 shows the top seven publishing countries in the selected research field, along with the number of publications and the most cited papers. The main country in publishing articles is China, specifically 76.8%, with 482 publications (Figure 9) which is three quarters of the total. It shows the substantial interest in this field, particularly when compared to other countries that are considerably distant from China. The six countries that follow China are the USA (5.9%), England (3.7%), France (3.7%), Czech Republic (3.2%), Australia (2.7%), and Spain (2.5%).

Table 3. Details of the seven countries with the highest impact of MPC.

Country	Maximum Number of Citations	Title	Authors	Reference
China	198	Factors that affect the properties of magnesium phosphate cement	Li Yue, Chen Bing	[60]
USA	146	Influence of fly ash on compressive strength and micro-characteristics of magnesium potassium phosphate cement mortars	Biwan Xu, Hongyan Ma, Hongyu Shao, Zongjin Li, Barbara Lothenbach	[61]
England	486	Magnesia-Based Cements: A Journey of 150 Years, and Cements for the Future?	Sam A. Walling, John L. Provis	[51]
France	126	On the influence of Mg/P ratio on the properties and durability of magnesium potassium phosphate cement pastes	Mathieu Le Rouzic, Thierry Chaussadent, Lavinia Stefan, Mickaël Saillio	[62]
Czech Republic	58	Preparation of magnesium phosphate cement by recycling the product of thermal transformation of asbestos containing wastes.	Alberto Viani, Alessandro F. Gualtieri	[63]
Australia	77	Red mud-enhanced magnesium phosphate cement for remediation of Pb and As contaminated soil	Lei Wang, Liang Chen, Binglin Guo, Daniel C.W. Tsang, Longbin Huang, Yong Sik Ok, Viktor Mechtcherine	[64]
Spain	45	Preliminary study of the mechanical and hygrothermal properties of hemp-magnesium phosphate cements	Ricardo del Valle-Zermeño, Jean Emmanuel Aubert, Aurélie Laborel-Préneron, Joan Formosa, Josep Maria Chimenos	[41]

While China leads in overall contributions to this field, considering the population density of each country reveals that the United States has the highest number of publications.

The top four authors with the highest number of publications on MPC are Chen Bing with 58 articles (9.2%), Li Yue with 34 articles (5.4%), Qian Jueshi with 32 articles (5.1%), and Jian-Ming Yang with 31 articles (4.9%). Chen Bing started publishing in 2020, Li Yue in 1999, Qian Jueshi in 1999, and Jian-Ming Yang in 2009; therefore, it is observed that this field of research is increasingly gaining more maturity and more relevance. Table 4 illustrates various indicators of the top authors, including their affiliation, number of publications, number of citations, and the H-index. Finally, the three most recurring affiliations in the publications are Shanghai Jiao Tong University (10.2%), Chongqing University (6.7%), and Beijing University of Technology (4.9%).

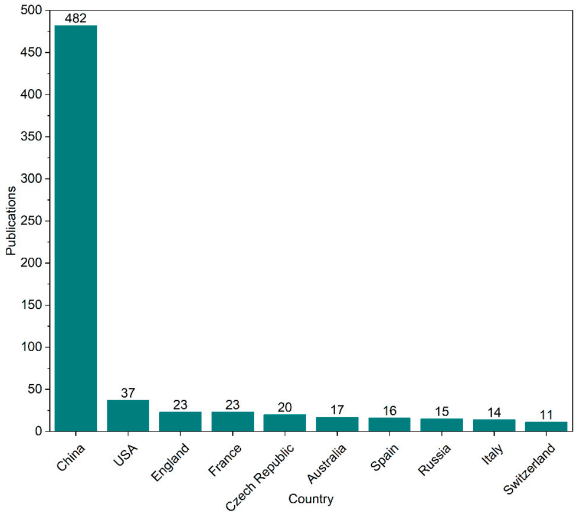

Figure 9. Number of publications from the most relevant countries.

Table 4. Authors with a significant impact in the MPC field.

Author	Affilation	Nº Publications	Citations	H-Index
Chen Bing	Shanghai Jiaotong University, Shanghai, China	235	9103	51
Li Yue	Beijing University of Technology, Beijing, China	239	2403	31
Qian Jueshi	Chongqing University, Chongqing, China	227	3945	36
Jian-Ming Yang	Sanjiang University, Nanjing, China	64	1077	17

Table 5 shows the three most impactful publications for each of the four most prominent authors in this research area, along with their titles, citations, publication years, and references.

The highest number of citations related to this selection occurred in 2023, reaching 3508 citations, as demostrated in Figure 10.

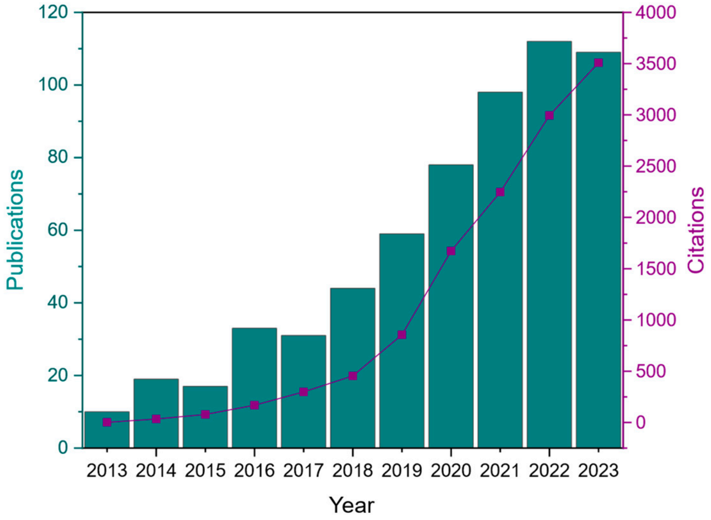

Figure 10. Times cited and publications over time on MPC.

Table 5. Most cited publications by the four authors with the most impact.

Author	Title	Citations	Year	Reference
Chen Bing	Research progresses on magnesium phosphate cement: A-review.	151	2019	[65]
	A comprehensive study of basalt fiber reinforced magnesium phosphate cement incorporating ultrafine fly ash.	128	2019	[66]
	Experimental research on magnesium phosphate cements modified by red mud.	116	2020	[67]
Li Yue	Effects of fly ash and quartz sand on water-resistance and salt-resistance of magnesium phosphate cement.	97	2016	[68]
	Experimental study on mechanical properties and fracture toughness of magnesium phosphate cement.	75	2015	[69]
	The effect of slag on the properties of magnesium potassium phosphate cement.	56	2016	[70]
Qian Jueshi	Influence of fly ash and metakaolin on the microstructure and compressive strength of magnesium potassium phosphate cement paste.	147	2018	[71]
	Effect of early hydration temperature on hydration product and strength development of magnesium phosphate cement (MPC).	110	2015	[72]
	Bond behavior and interfacial micro-characteristics of magnesium phosphate cement onto old concrete substrate.	94	2018	[73]
Jian-Ming Yang	Research progresses in magnesium phosphate cement-based materials.	103	2014	[74]
	Effect of waterglass on water stability of potassium magnesium phosphate cement paste.	88	2014	[75]
	Effect of curing regime on water resistance of magnesium–potassium phosphate cement.	74	2017	[76]

Table 6 presents the five most cited publications, all of which are highly relevant to the research field. The top-ranked publication is a review, while the remaining four are research articles.

Table 6. Highly relevant publications.

Citations	Tittle	Authors	Reference	Year	Country
486	Magnesia-Based Cements: A Journey of 150 Years, and Cements for the Future?	Walling, SA, Provis, JL	[51]	2016	England
198	Factors that affect the properties of magnesium phosphate cement	Li Yue, Chen Bing	[60]	2013	China
173	Magnesium potassium phosphate cement paste: Degree of reaction, porosity and pore structure	Hongyan Ma, Biwan Xu, Zongjin Li	[77]	2014	China
172	Effects of water content, magnesia-to-phosphate molar ratio and age on pore structure, strength and permeability of magnesium potassium phosphate cement paste	Hongyan Ma, Biwan Xu, Jun Liu, Huafu Pei, Zongjin Li	[78]	2014	China
151	Research progresses on magnesium phosphate cement: A review	M. Aminul Haque, Chen Bing	[65]	2019	China

Finally, a keyword map was created for all the selected publications to visualize the trends and advancements in keywords and is shown in Figure 11. It highlights the most frequently used keywords, including “Magnesium phosphate cement”, “Magnesium potassium phosphate cement", and "Microstructure". The map showcases different circles, each representing a keyword within the chosen research field. The connecting lines between circles indicate the number of publications featuring each keyword. The size of each keyword is directly proportional to its frequency of occurrence in the selected publications. Larger keywords represent terms that appear more frequently, while smaller keywords correspond to less frequently mentioned terms. Consequently, keywords with smaller font sizes may be less legible, reflecting their lower prominence within the research field. Furthermore, the color scheme represents the appearance year of the keyword. Specifically, yellow refers to recent terms, while blue corresponds to older ones. After evaluating the trends and the specific keywords such as porosity, durability, and 3D printing, it becomes evident that there has been notable improvement and progress in this field in recent years. The keywords "Microstructure", "Compressive strength", and "Mechanical properties" are closely linked to material properties and characteristics, which, in turn, can be linked to the application requirements.

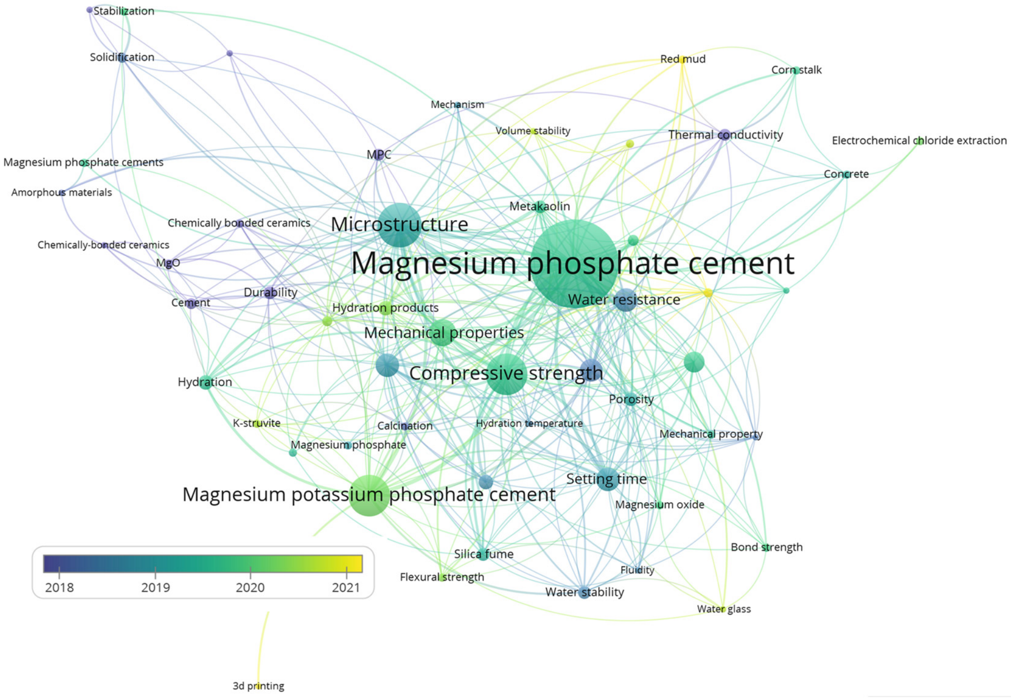

Figure 11. Keyword map of MPC.

3. Alternative Cements

The following section presents alternative materials to high-purity MgO. The materials presented are industrial by-products and waste that have been identified in the literature as potential alternatives for the development of MPC. The methods of obtaining and conditioning these materials for use as a source of magnesium oxide to obtain MPC are described. Significantly, although the conditioning processes of these secondary materials involve an energy cost, if pure MgO is used, a thermal treatment at high temperatures (above 1000 °C) must be carried out in order to achieve adequate reactivity and thus the correct formation of the cementitious matrix.

3.1. Low-Grade Magnesium Oxide (LG-MgO)

Magnesite ($MgCO_3$) is one of the most important raw material sources for magnesia refractory production [79]. After its calcination, two principal products are commonly obtained, calcined magnesite and sintered magnesite. Below are the sequential steps involved in obtaining MgO [79]:

1. Mineral extraction: Several minerals are extracted from different opencast mines rich in $MgCO_3$. Magnesite is the main source of magnesium, although it is also possible to obtain it from seawater and brines such as $Mg(OH)_2$. Then, the minerals are ground.
2. Separation: The minerals are discharged into hoppers at the factory. To remove impurities in the mineral, it is classified by size through a classifier/washer, obtaining a carbonate that can be used in the process. The minerals classified are separated employing two wet sieves, obtaining four fractions (greater than 12 mm, 4–12 mm, 1–4 mm, and 0.3–1 mm).
3. Enrichment of magnesium carbonate: The two smaller fractions are sent to cyclones, where the minerals are dehydrated. This fraction cannot be enriched more, being stored to feed the ovens or being dried and sold as carbonate. The two greater fractions pass along conveyor belts to enrich the treatment plant for dense media that contains water and minerals. These fractions are also used to feed the ovens.
4. Calcination and/or sintering of magnesium carbonate to obtain MgO: The separated minerals are added to different rotating cylindrical kilns at temperatures between 1100 °C and 1950 °C. The finer materials are compacted because, otherwise, the current from the furnace would drag them away. The thermal decomposition that occurs in the kiln is shown below (Equation (4)):

$$MgCO_{3(s)} \rightarrow MgO_{(s)} + CO_{2(g)} \tag{4}$$

Depending on the calcination temperature, MgO is produced with different reactivity, with the following use conditions:

- The caustic calcined magnesite (CCM), high reactive MgO, is treated around 1300 °C. It is used in agriculture, livestock applications, and innovative products for the environment.
- The sintered magnesite or dead burned magnesite (DBM) is treated at temperatures higher than 1800 °C. It is essential for the steel industry in refractory materials manufacturing.

The high-temperature air current circulates in a direction opposite to the movement of the material. The combustion gases are led to a purification system before their emission into the atmosphere, where the flying particles are retained, initially in a system of cyclones and later in a bag filter. The by-product, mainly composed of low-grade or low-content MgO, is collected as cyclone dust, as shown in Figure 12, named low-grade magnesium oxide (LG-MgO). LG-MgO is an industrial by-product obtained from the calcination process of natural $MgCO_3$ to produce MgO. Then, LG-MgO plays a crucial role in the production of MgO.

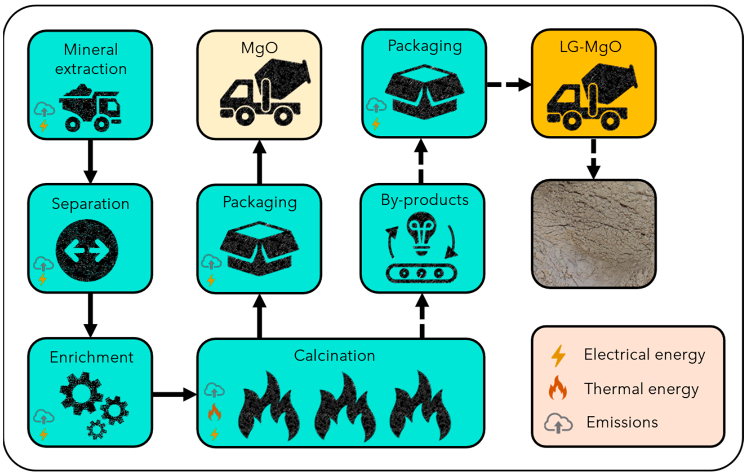

Figure 12. Simplified flow diagram for producing LG-MgO at Magnesitas Navarras S.A. (Zubiri-Navarra, Spain).

LG-MgO has different environmental applications such as stabilization of metal-contaminated soils, desulfurization of gases, production of hydromagnesite, and for CBPC development as a precursor for MKPC, among others [80]. Using LG-MgO instead of pure MgO has many benefits. Not only does it contribute to environmental sustainability by valorizing industrial by-products, but it also presents a significant economic benefit, being ten times more cost-effective [43,44]. Taking this into account, the production of 1 ton of MgO from $MgCO_3$ results in approximately 1.08 tons of carbon dioxide emissions. This translates to a higher emission level compared to the emissions from OPC [81].

3.2. Tundish Deskulling Waste

Steel production significantly increased in the last decade [82,83]. Steel is indispensable for numerous sectors, including energy, transportation, and construction. This material is usually produced in a basic oxygen furnace or in an electric arc furnace [83]. Refractory materials are essential for steel manufactories. The function of refractory materials is to form a protective lining layer in high-temperature containers. The final refractory material depends on the main materials and its composition. Refractory materials can be acid, neutral, or basic. Refractories based on magnesia (MgO) are basic ones and present resistance to steelmaking slags [84]. Pure MgO is used in steelmaking industries due to its excellent slag corrosion resistance, thermal shock resistance, and low corrosion [85]. Around 90% of the world's steel production goes through a continuous casting process [86]. Tundish mass is an indispensable component for regulating the right amount of molten steel. It is the last metallurgical container where the steel liquid flows from the ladle to the continuous casting mold before solidifying. The interactions between molten steel and tundish are fundamental for the steel industry [87]. Thus, the material and design of the tundish are crucial in defining the composition and quality of the steel [86]. The flow field within the tundish plays a critical role in removing any inclusion [88]. Due to the importance of this material, many innovations have been introduced in the steelmaking sector [89,90].

Tundish is usually recovered from a basic refractory material, known as tundish mass, with more than 60% MgO [84]. The composition of refractory material for tundish is essential because it must present the correct property to ensure the quality of the steel. A fundamental property is thermal shock resistance.

The refractory material (tundish mass) used in the steel industry deteriorates over time and becomes waste, referred to as tundish deskulling waste (TUN), which is disposed of in landfills [36]. Consequently, there is a global issue that requires management and prevention to avoid its disposal in landfill. Nevertheless, TUN could be considered a by-product, given its considerable potential for further processing and value addition [91,92]. The entire scientific environment is looking for applications for this waste to reduce the environmental footprint. In addition, waste or by-products used as raw materials avoids the impact associated with natural mineral resource extraction. Hence, TUN can be used as a MgO source, but it must be properly conditioned to achieve an adequate quality with the desired particle size to be used as a component of the MPC [91]. The TUN conditioning process, provided by Magnesitas Navarras, S.A., is based on different steps and shown in Figure 13:

1. Collection and manual separation. Tundish deskulling waste (TUN) is collected in the steel industry after its use. Fractions of visible undesirables are removed manually before moving to the next phase. Once the raw material is picked up, it is transported by truck to the conditioning plant.

2. Screening. The material is sieved into two different size fractions, pebbles larger than 10 mm, named blocks, and all other grain sizes smaller than 10 mm known as fines. From now on and until further notice, these two fractions will be treated separately.
3. Grinding. Each fraction is automatically crushed and sieved into two particle sizes, firstly 1 to 3 mm and then particles below 1 mm.
4. Magnetic separation. Magnetic separation is the final stage in the conditioning plant. Both fractions go separately through a magnetic machine to remove part of the remaining steel to increase the purity of the outgoing materials. After separating the magnetic and non-magnetic parts from the fractions, the non-magnetic fractions are gathered once again.

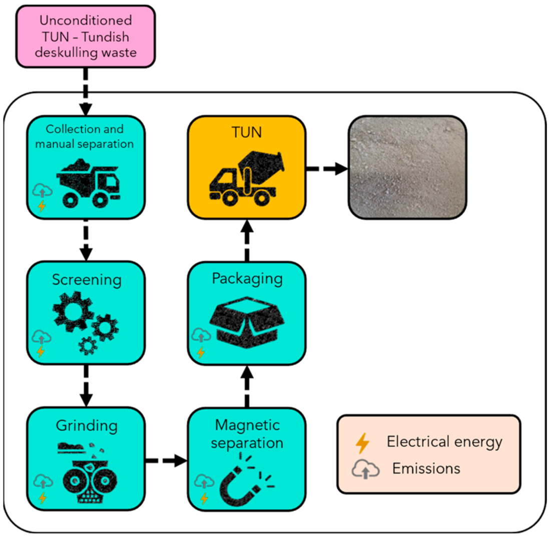

Figure 13. Conditioning process of TUN.

Afterwards, the non-magnetic material is transported by truck to another plant to mix it with the other components to obtain MPC considering the specific proportions.

Anyway, this process is specifically designed to utilize the material as a source of MgO for the development of MPC. However, in the case of Magnesitas Navarras, this fraction is used as feedstock for the furnace.

3.3. Boron-Containing Magnesium Oxide By-Product (B-MgO)

Lithium is emerging as a pivotal energy material, prominently employed in lithium-ion batteries (LiBs) for electric vehicles [93]. These new vehicles have the potential to reduce the environmental footprint associated with conventional fossil-fuel vehicles. Lithium is a key component to the energy transition in the coming years and, for this reason, nowadays it is one of the most critical metals.

The global Li content production in 2020 amounted to 82·103 metric tons, and it is estimated to increase due to the new revolution in the transportation sector. Consequently, a substantial volume of waste and by-products are and will be generated. Li is produced from brine (Li_2CO_3) or from hard-rock ore (concentrate of Li_2CO_3 and LiOH) [94]. The brines are the main source of Li, such as from salt lakes brines, for their cheaper production cost and their availability [95].

Approximately 40% of the world's Li_2CO_3 production in 2020 was sourced from brine-based resources [94]. Li_2CO_3 production is based on different processes, shown in Figure 14 [95]. Specifically, the process starts with Li-containing brines, followed by Li-containing $MgCl_2$, and continuing with Li-containing MgO, to obtain the dilute LiCl solution that will later be used to obtain LiCl concentrate to get Li_2CO_3 [96].

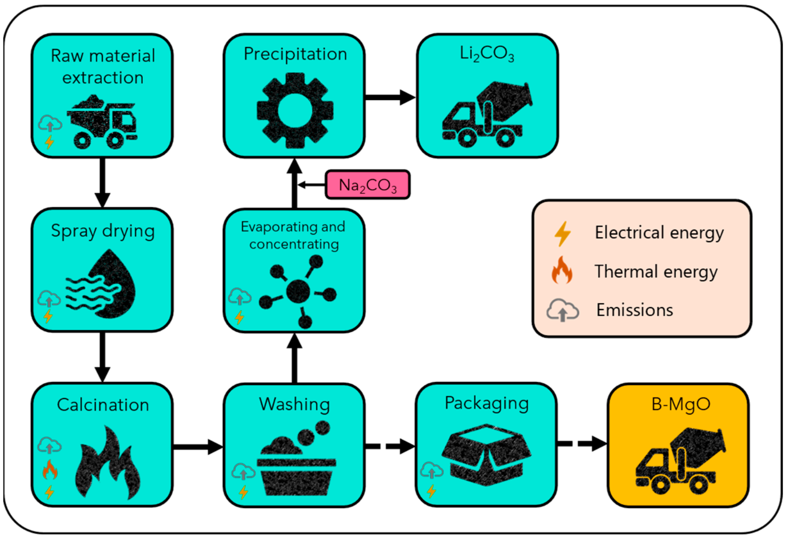

Figure 14. Production of Li_2CO_3 [97,98].

One of the by-products of the production of $LiCO_3$ from salt lakes is boron-containing MgO, known as a B-MgO [58]. B-MgO needs to undergo calcination within a temperature range between 800 °C and 1400 °C to achieve the desired surface area, ensuring the appropriate reactivity for its use as a raw material [99,100]. Notably, the calcination conditions are totally linked to the properties of the MgO source. The main components of B-MgO by-product are MgO and trimagnesium diborate ($Mg_3B_2O_6$) [96]. Ideally, the optimal approach would involve removing impurities from the by-product. Despite this, the high cost associated with the purification process prevents the separation of boron and magnesium [101].

In the coming years, this technology is expected to mature and become increasingly significant. Consequently, it is crucial to explore alternative approaches for developing new applications to employ the waste and by-products generated.

3.4. Magnesia Refractory Brick Waste (MRBW)

Magnesia refractory brick (MRB) is used in the metallurgy sector, due to its service conditions such as high fire resistance, high-temperature strength, and high absorption of thermomechanical stresses [102]. As a key component, its demand is expected to increase. It is applied to furnace equipment in high-temperature environments. After their useful life, the refractory materials must be replaced by others to guarantee operating conditions. It is at this point that magnesia refractory brick waste (MRBW) is produced.

MRBW is formed by different refractory materials based on MgO, MgO-C, MgO-Al_2O_3, MgO-CaO, MgO-SiO_2, or MgO-Cr_2O_3 [103,104]. The specific properties of the refractories may be tuned depending on their composition. Several studies demonstrate the high quality of MgO content in the composition of MRB. Then, it is an alternative and promising source of MgO to develop MPC [104–106].

Nevertheless, a conditioning process is essential to obtain an adequate granulometry, as shown in Figure 15. This process relies on crushing, sorting, and grinding procedures. Waste valorization is beneficial for avoiding landfilling treatment and reducing the environmental impact associated with the extraction of natural resources.

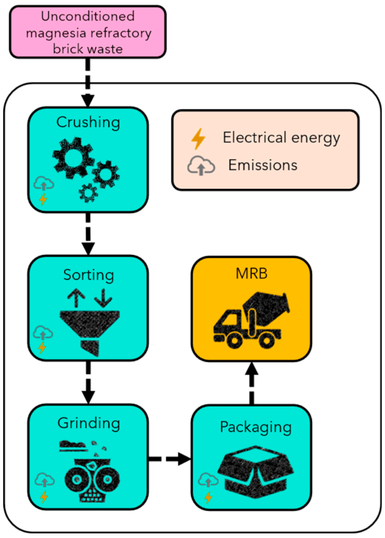

Figure 15. Process diagram of the conditioning process of MRBW.

3.5. Challenges and Future Considerations

Despite the numerous advantages of MPC developed with alternative sources, its implementation on a large industrial scale still faces certain challenges. Addressing these obstacles is essential to unlocking the potential of alternative materials for use in sustainable construction. Some of the most pressing challenges and future considerations to be addressed include:

1. Local resource availability: Ensuring the availability and quality of local raw materials is essential to standardize the production of MPC. Given the widespread availability of alternative sources across many regions, MPC offers several advantages, making it easier to adopt globally by utilizing locally sourced materials. However, the variability of resources can affect homogeneity and consequently the performance of the final product. Then, it is essential to develop strategies for sourcing and material characterization to ensure the viability and reliability of MPC formulations.
2. Alternative phosphate sources: The use of alternative phosphate sources is vital for enhancing sustainability and reducing costs. Identifying and optimizing secondary or recycled phosphate materials could mitigate dependence on primary resources while lowering the environmental footprint.
3. Pilot testing for properties and durability: Rigorous pilot-scale testing of MPC formulations is required to evaluate their mechanical properties, durability, and long-term performance under real-world conditions. These studies are essential for building confidence in MPC suitability for diverse applications.
4. Adoption barriers: Overcoming adoption barriers in the construction industry is a key challenge. This includes addressing cost considerations, adapting production techniques, meeting regulatory standards, and increasing awareness of MPC's environmental and performance benefits among stakeholders.

By addressing these challenges, MPC technology can advance toward becoming a widely adopted solution in sustainable construction practices. This progress would not only significantly reduce the environmental footprint of the construction industry but also promote the principles of a circular economy by integrating waste and by-product valorization and resource efficiency.

Table 7 provides an indicative comparison of chemical compositions and typical ranges of CO_2 emissions, illustrating the relative advantages of waste-derived MgO for

MPC production. Values are approximate due to variability in raw materials, processing conditions, and system boundaries.

Table 7. Comparative overview of the approximate chemical compositions and typical ranges of CO_2 emissions for different cement types and alternative raw materials.

Cement/Material	Main Chemical Components (Range)	Typical CO_2 Emissions (kg CO_2/ton Cement)	References
Ordinary Portland Cement (OPC)	CaO (~60–65%) SiO_2 (~20%) Al_2O_3 (~5–8%) Fe_2O_3 (~2–5%)	800–950	[107,108]
Calcium-Based Cements (CBCs)	CaO-rich phases Variable SiO_2 Variable Al_2O_3 Variable Fe_2O_3	700–900	[108,109]
Calcium–Phosphate Cements (CBPCs)	CaO + phosphate phases (e.g., $Ca_3(PO_4)_2$)	500–700	[108,109]
Magnesium Phosphate Cements (MPCs)	MgO (from various sources), $NH_4H_2PO_4$, phosphate phases	200–400	[51,108]
Boron-Containing MgO (B-MgO)	MgO with B_2O_3 traces	150–350	[108,110]
Magnesia Refractory Brick Waste (MRBW)	High MgO (>70%) Minor Fe_2O_3, Al_2O_3	100–250	[108,110]

4. Conclusions

This review has explored strategies to reduce the environmental footprint of the cement industry, with a particular focus on magnesium phosphate cement (MPC) as a sustainable alternative to ordinary Portland cement (OPC). The findings suggest that MPC could play a critical role in advancing low-carbon, resource-efficient solutions for the construction sector. Within the context of urban development, the following conclusions can be drawn:

- MPCs represent a promising alternative binder to OPC, offering rapid setting, high early strength, and durability, making them particularly suitable for diverse urban infrastructure applications, including repair, prefabrication, and emergency construction.
- The use of industrial by-products and waste materials as alternative sources of MgO in MPC formulations contributes to more circular, locally adapted urban material flows, aligning with sustainable urban resource management and waste valorization strategies.
- Adoption of MPC-based systems can support cities' efforts to reduce greenhouse gas emissions and mitigate climate change impacts through lower embodied carbon in construction materials.
- Advancing fully sustainable alternative MPC systems will require continued research and innovation of secondary phosphate sources, particularly in identifying and validating new and sustainable phosphate sources, which could be integrated into urban and regional waste recovery systems, promoting local circular economy models.
- Ensuring consistent technical performance while managing the variability of waste-based materials is essential, particularly in densely populated urban environments where structural reliability and regulatory compliance are critical.
- A multidisciplinary approach—combining materials science, urban planning, environmental policy, and industrial ecology—is vital to fully evaluate and implement alternative cementitious systems within urban settings.
- Future studies should not only assess technical and environmental aspects but also explore how these materials contribute to broader urban sustainability goals, including resilience, resource efficiency, and the reduction of construction-related emissions in cities.

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Abbreviations

The following abbreviations are used in this manuscript:

MPC	Magnesium phosphate cement
MgO	Magnesium oxide
LG-MgO	Low-grade MgO
TUN	Tundish deskulling waste
B-MgO	Boron–magnesium oxide
MRB	Magnesia refractory brick waste
GHG	Greenhouse gase
OPC	Ordinary Portland cement
WoS	Web of Science
LC3	Limestone-calcined clay cement
AAC	Alkali-activated cement
MSW	Municipal solid waste
BFS	Blast furnace slag
FA	Fly ash
CAC	Calcium aluminate cement
CSAC	Calcium sulfoaluminate cement
BC	Belite cement
CBC	Chemically bonded ceramic
CBPC	Chemically bonded phosphate cement
ABC	Acid–base cement
MKP, KH_2PO_4	Monopotassium phosphate
MKPC	Magnesium potassium phosphate cement
K-struvite	$MgKPO_4 \cdot 6H_2O$
DBM	Dead burned magnesia
$MgCO_3$	Magnesite
CCM	Caustic calcined magnesite

References

1. Eurostat—Statistics Explained, Waste Statistics. 2020. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Waste_statistics#Total_waste_generation (accessed on 7 November 2023).
2. International Energy Agency, World Energy Outlook. 2021. Available online: https://www.iea.org/search?q=World%20Energy%20Outlook%202021 (accessed on 7 November 2023).
3. Favier, A.; De Wolf, C.; Scrivener, K.; Habert, G. *A Sustainable Future for the European Cement and Concrete Industry: Technology Assessment for Full Decarbonisation of the Industry by 2050*; ETH: Zurich, Switzerland, 2018. [CrossRef]
4. Eurostat Statistics Explained, Energy Statistics—An Overview. 2021. Available online: https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Energy_statistics_-_an_overview&oldid (accessed on 7 November 2023).
5. International Energy Agency. Major Growth of Clean Energy Limited the Rise in Global Emissions in 2023. Available online: https://www.iea.org/news/major-growth-of-clean-energy-limited-the-rise-in-global-emissions-in-2023 (accessed on 7 November 2023).
6. Statista. Production Volume of Cement Worldwide from 1995 to 2022. 2023. Available online: https://www.statista.com/statistics/1087115/global-cement-production-volume/ (accessed on 7 November 2023).
7. Tregambi, C.; Solimene, R.; Montagnaro, F.; Salatino, P.; Marroccoli, M.; Ibris, N.; Telesca, A. Solar-driven production of lime for ordinary Portland cement formulation. *Sol. Energy* **2018**, *173*, 759–768. [CrossRef]
8. The European Cement Association, Cementing the European Green Deal. International Energy Agency, Cement. Available online: https://www.iea.org/energy-system/industry/cement#overview (accessed on 16 March 2024).
9. International Energy Agency, Cement. Available online: https://www.iea.org/energy-system/industry/cement#tracking (accessed on 4 March 2024).
10. International Energy Agency, Cement Report. Available online: https://www.iea.org/reports/cement (accessed on 4 March 2024).
11. Gladwin, A.; Alex, A.; Kedir, T. Gebrehiwet Tewele, Review on effects of graphene oxide on mechanical and microstructure of cement-based materials. *Constr. Build. Mater.* **2022**, *360*, 129609. [CrossRef]
12. Cadix, A.; James, S. Cementing additives. In *Fluid Chemistry, Drilling and Completion*; Elsevier: Amsterdam, The Netherlands, 2022; pp. 187–254. [CrossRef]
13. Wagh, A.S. Recent Progress in Chemically Bonded Phosphate Ceramics. *ISRN Ceram.* **2013**, *2013*, 983731. [CrossRef]
14. Kusuma, R.T.; Hiremath, R.B.; Rajesh, P.; Kumar, B.; Renukappa, S. Sustainable transition towards biomass-based cement industry: A review. *Renew. Sustain. Energy Rev.* **2022**, *163*, 112503. [CrossRef]
15. Torres-Carrasco, M.; Puertas, F. La activación alcalina de diferentes aluminosilicatos como una alternativa al Cemento Portland: Cementos activados alcalinamente o geopolímeros. *Rev. Ing. Constr.* **2017**, *32*, 5–12. [CrossRef]
16. International Energy Agency, Global Thermal Energy Intensity and Fuel Consumption of Clinker Production in the Net Zero Scenario, 2015–2030. Available online: https://www.iea.org/data-and-statistics/charts/global-thermal-energy-intensity-and-fuel-consumption-of-clinker-production-in-the-net-zero-scenario-2015-2030 (accessed on 4 March 2024).
17. He, Z.; Zhu, X.; Wang, J.; Mu, M.; Wang, Y. Comparison of CO_2 emissions from OPC and recycled cement production. *Constr. Build. Mater.* **2019**, *211*, 965–973. [CrossRef]
18. Alsalman, A.; Assi, L.N.; Kareem, R.S.; Carter, K.; Ziehl, P. Energy and CO_2 cherm emission assessments of alkali-activated concrete and Ordinary Portland Cement concrete: A comparative analysis of different grades of concrete. *Clean. Environ. Syst.* **2021**, *3*, 100047. [CrossRef]
19. Rocha, J.H.A.; Filho, R.D.T.; Cayo-Chileno, N.G. Sustainable alternatives to CO_2 reduction in the cement industry: A short review. *Mater. Today Proc.* **2022**, *57*, 436–439. [CrossRef]
20. Hassan, A.M.S.; Shoukry, H.; Perumal, P.; El-razik, M.M.A.; Aly, R.M.H.; Alzahrani, A.M.Y. Evaluation of the thermo-physical, mechanical, and fire resistance performances of limestone calcined clay cement (LC3)-based lightweight rendering mortars. *J. Build. Eng.* **2023**, *71*, 106495. [CrossRef]
21. Scrivener, K.; Martirena, F.; Bishnoi, S.; Maity, S. Calcined clay limestone cements (LC3). *Cem. Concr. Res.* **2018**, *114*, 49–56. [CrossRef]
22. Mañosa, J.; Calderón, A.; Salgado-Pizarro, R.; Maldonado-Alameda, A.; Chimenos, J.M. Research evolution of limestone calcined clay cement (LC3), a promising low-carbon binder—A comprehensive overview. *Heliyon* **2024**, *10*, e25117. [CrossRef] [PubMed]
23. Khan, M.; Lao, J.; Ahmad, M.R.; Kai, M.F.; Dai, J.G. The role of calcium aluminate cement in developing an efficient ultra-high performance concrete resistant to explosive spalling under high temperatures. *Constr. Build. Mater.* **2023**, *384*, 131469. [CrossRef]
24. Xu, Y.; He, T.; Ma, X.; Luo, R. The influence of calcium sulphoaluminate cement on the hydration process of cement paste mixed with alkali free liquid accelerator. *Mater. Today Commun.* **2022**, *33*, 104622. [CrossRef]
25. Cuesta, A.; Ayuela, A.; Aranda, M.A.G. Belite cements and their activation. *Cem. Concr. Res.* **2021**, *140*, 106319. [CrossRef]
26. Goncharov, A.; Zhutovsky, S. Eco-friendly belite cement from crude calcareous oil shale with low calorific value. *Cem. Concr. Res.* **2022**, *159*, 106874. [CrossRef]
27. Jiang, C.; Jiang, L.; Li, S.; Tang, X.; Zhang, L. Impact of cation type and fly ash on deterioration process of high belite cement pastes exposed to sulfate attack. *Constr. Build. Mater.* **2021**, *286*, 122961. [CrossRef]

28. Huete-Hernández, S.; Maldonado-Alameda, A.; Giro-Paloma, J.; Chimenos, J.M.; Formosa, J. Fabrication of sustainable magnesium phosphate cement micromortar using design of experiments statistical modelling: Valorization of ceramic-stone-porcelain containing waste as filler. *Ceram. Int.* **2021**, *47*, 10905–10917. [CrossRef]
29. Huete-Hernández, S.; Maldonado-Alameda, A.; Alfocea-Roig, A.; Giro-Paloma, J.; Chimenos, J.M.; Formosa, J. Sustainable magnesium phosphate micromortars formulated with PAVAL® alumina by-product as micro-aggregate. *Bol. Soc. Esp. Ceram. Vidr.* **2023**, *62*, 543–557. [CrossRef]
30. Zhang, Q.; Cao, X.; Ma, R.; Sun, S.; Fang, L.; Lin, J.; Luo, J. Solid waste-based magnesium phosphate cements: Preparation, performance and solidification/stabilization mechanism. *Constr. Build. Mater.* **2021**, *297*, 123761. [CrossRef]
31. Kinnunen, P.; Ismailov, A.; Solismaa, S.; Sreenivasan, H.; Räisänen, M.L.; Levänen, E.; Illikainen, M. Recycling mine tailings in chemically bonded ceramics—A review. *J. Clean. Prod.* **2018**, *174*, 634–649. [CrossRef]
32. Wagh, A.S. Introduction to Chemically Bonded Ceramics. In *Chemically Bonded Phosphate Ceramics*; Elsevier: Amsterdam, The Netherlands, 2016; pp. 1–16. [CrossRef]
33. Huang, X.; Wu, H.; Lu, D. Preparation of novel chemically bonded ceramics with steel slag and potassium hydrogen oxalate. *J. Hazard. Mater.* **2021**, *403*, 124042. [CrossRef]
34. Colorado, H.A.; Pleitt, J.; Hiel, C.; Yang, J.M.; Hahn, H.T.; Castano, C.H. Wollastonite based-Chemically Bonded Phosphate Ceramics with lead oxide contents under gamma irradiation. *J. Nucl. Mater.* **2012**, *425*, 197–204. [CrossRef]
35. Balaguera, C.A.C.; Botero, M.A.G. Engineering applications of chemically-bonded phosphate ceramics. *Ing. Investig.* **2019**, *39*, 10–19. [CrossRef]
36. Machado, A.P.; Arcaro, S.; Raupp-Pereira, F.; Bergmann, C.P.; Montedo, O.R.K. Chemically-Bonded Magnesium Phosphate Ceramics from Magnesium Oxide-Graphite Refractory Brick Waste. *Mater. Res.* **2021**, *24*, e20210162. [CrossRef]
37. Formosa, J. Formulaciones de Nuevos Morteros y Cementos Especiales Basadas en Suproductos de Magnesio. Ph.D. Thesis, Universitat de Barcelona, Barcelona, Spain, 2012.
38. Yan, C.; Ma, H.; Luo, Z.; Zhou, X.; Wang, L. Influence of Phosphorus Sources on the Compressive Strength and Microstructure of Ferronickel Slag-Based Magnesium Phosphate Cement. *Materials* **2022**, *15*, 1965. [CrossRef]
39. Zheng, Y.; Zhou, Y.; Huang, X.; Luo, H. Effect of raw materials and proportion on mechanical properties of magnesium phosphate cement. *J. Road Eng.* **2022**, *2*, 243–251. [CrossRef]
40. Meng, X.; Jiang, Y.; Chen, B.; Wang, L. Research progress on the setting time and solidification mechanism of magnesium phosphate cement: A review. *Constr. Build. Mater.* **2023**, *408*, 133612. [CrossRef]
41. Del Valle-Zermeño, R.; Aubert, J.E.; Laborel-Préneron, A.; Formosa, J.; Chimenos, J.M. Preliminary study of the mechanical and hygrothermal properties of hemp-magnesium phosphate cements. *Constr. Build. Mater.* **2016**, *105*, 62–68. [CrossRef]
42. Wang, M.; Liang, L.; Liu, Q.; Liang, X.; Guo, H.; Li, Z.; Liang, R.; Sun, G. Influence of dipotassium hydrogen phosphate on properties of magnesium potassium phosphate cement. *Constr. Build. Mater.* **2022**, *320*, 126283. [CrossRef]
43. Amiandamhen, S.O.; Meincken, M.; Tyhoda, L. Phosphate bonded natural fibre composites: A state of the art assessment. *SN Appl. Sci.* **2019**, *1*, 910. [CrossRef]
44. Ribeiro, D.V.; Paula, G.R.; Morelli, M.R. Effect of boric acid content on the properties of magnesium phosphate cement. *Constr. Build. Mater.* **2019**, *214*, 557–564. [CrossRef]
45. Ding, Z.; Li, Y.-Y.; Lu, C.; Liu, J. An Investigation of Fiber Reinforced Chemically Bonded Phosphate Ceramic Composites at Room Temperature. *Materials* **2018**, *11*, 858. [CrossRef]
46. Tao, Y.; Zhenyu, L.; Chunrong, R.; Yuanyuan, W.; Zhichao, H.; Xin, H.; Jie, W.; Mengliang, L.; Qiubai, D.; Khan, K.; et al. Study on solidification properties of chemically bonded phosphate ceramics for cesium radionuclides. *Ceram. Int.* **2020**, *46*, 14964–14971. [CrossRef]
47. Li, Y.; Zhang, G.; Wang, Z.; Guan, Z. Experimental-computational approach to investigate compressive strength of magnesium phosphate cement with nanoindentation and finite element analysis. *Constr. Build. Mater.* **2018**, *190*, 414–426. [CrossRef]
48. Li, Y.; Sun, J.; Chen, B. Experimental study of magnesia and M/P ratio influencing properties of magnesium phosphate cement. *Constr. Build. Mater.* **2014**, *65*, 177–183. [CrossRef]
49. Gardner, L.J.; Walling, S.A.; Corkhill, C.L.; Bernal, S.A.; Lejeune, V.; Stennett, M.C.; Provis, J.L.; Hyatt, N.C. Temperature transformation of blended magnesium potassium phosphate cement binders. *Cem. Concr. Res.* **2021**, *141*, 106332. [CrossRef]
50. Gardner, L.J.; Walling, S.A.; Lawson, S.M.; Sun, S.; Bernal, S.A.; Corkhill, C.L.; Provis, J.L.; Apperley, D.C.; Iuga, D.; Hanna, J.V.; et al. Characterization of and Structural Insight into Struvite-K, MgKPO4·6H2O, an Analogue of Struvite. *Inorg. Chem.* **2020**, *60*, 195–205. [CrossRef]
51. Walling, S.A.; Provis, J.L. Magnesia-Based Cements: A Journey of 150 Years, and Cements for the Future? *Chem. Rev.* **2016**, *116*, 4170–4204. [CrossRef]
52. Leng, D.; Li, X.; Lv, Y.; Tan, H.; Li, N.; Liu, Z.; Jiang, W.; Jiang, D. Cesium immobilization by K-struvite crystal in aqueous solution: Ab initio calculations and experiments. *J. Hazard. Mater.* **2020**, *387*, 121872. [CrossRef]

53. Momma, K.; Izumi, F. VESTA 3 for three-dimensional visualization of crystal, volumetric and morphology data. *J. Appl. Crystallogr.* **2011**, *44*, 1272–1276. [CrossRef]
54. Fan, S.; Chen, B. Experimental study of phosphate salts influencing properties of magnesium phosphate cement. *Constr. Build. Mater.* **2014**, *65*, 480–486. [CrossRef]
55. Bullard, J.W.; Jennings, H.M.; Livingston, R.A.; Nonat, A.; Scherer, G.W.; Schweitzer, J.S.; Scrivener, K.L.; Thomas, J.J. Mechanisms of cement hydration. *Cem. Concr. Res.* **2011**, *41*, 1208–1223. [CrossRef]
56. Huang, X.; Liu, G.; Zheng, Y.; Luo, H. The performance of magnesium phosphate cement in negative temperature environment: A state-of-the-art review. *J. Build. Eng.* **2023**, *76*, 107278. [CrossRef]
57. Le Rouzic, M.; Chaussadent, T.; Platret, G.; Stefan, L. Mechanisms of k-struvite formation in magnesium phosphate cements. *Cem. Concr. Res.* **2017**, *91*, 117–122. [CrossRef]
58. Fang, B.; Hu, Z.; Shi, T.; Liu, Y.; Wang, X.; Yang, D.; Zhu, K.; Zhao, X.; Zhao, Z. Research progress on the properties and applications of magnesium phosphate cement. *Ceram. Int.* **2023**, *49*, 4001–4016. [CrossRef]
59. Salgado-Pizarro, R.; Calderón, A.; Svobodova-Sedlackova, A.; Fernández, A.I.; Barreneche, C. The relevance of thermochemical energy storage in the last two decades: The analysis of research evolution. *J. Energy Storage* **2022**, *51*, 104377. [CrossRef]
60. Li, Y.; Chen, B. Factors that affect the properties of magnesium phosphate cement. *Constr. Build. Mater.* **2013**, *47*, 977–983. [CrossRef]
61. Xu, B.; Ma, H.; Shao, H.; Li, Z.; Lothenbach, B. Influence of fly ash on the compressive strength and micro-characteristics of magnesium potassium phosphate cement mortars. *Cem. Concr. Res.* **2017**, *99*, 86–94. [CrossRef]
62. Le Rouzic, M.; Chaussadent, T.; Stefan, L.; Saillio, M. On the influence of Mg/P ratio on the properties and durability of magnesium potassium phosphate cement pastes. *Cem. Concr. Res.* **2017**, *96*, 27–41. [CrossRef]
63. Viani, A.; Gualtieri, A.F. Preparation of magnesium phosphate cement by recycling the product of thermal transformation of asbestos containing wastes. *Cem. Concr. Res.* **2014**, *58*, 56–66. [CrossRef]
64. Wang, L.; Chen, L.; Guo, B.; Tsang, D.C.W.; Huang, L.; Ok, Y.S.; Mechtcherine, V. Red mud-enhanced magnesium phosphate cement for remediation of Pb and As contaminated soil. *J. Hazard. Mater.* **2020**, *400*, 123317. [CrossRef]
65. Haque, M.A.; Chen, B. Research progresses on magnesium phosphate cement: A review. *Constr. Build. Mater.* **2019**, *211*, 885–898. [CrossRef]
66. Ahmad, M.R.; Chen, B.; Yu, J. A comprehensive study of basalt fiber reinforced magnesium phosphate cement incorporating ultrafine fly ash. *Compos. Part B Eng.* **2019**, *168*, 204–217. [CrossRef]
67. Liu, Y.; Qin, Z.; Chen, B. Experimental research on magnesium phosphate cements modified by red mud. *Constr. Build. Mater.* **2020**, *231*, 117131. [CrossRef]
68. Li, Y.; Shi, T.; Li, J. Effects of fly ash and quartz sand on water-resistance and salt-resistance of magnesium phosphate cement. *Constr. Build. Mater.* **2016**, *105*, 384–390. [CrossRef]
69. Li, Y.; Li, Y.; Shi, T.; Li, J. Experimental study on mechanical properties and fracture toughness of magnesium phosphate cement. *Constr. Build. Mater.* **2015**, *96*, 346–352. [CrossRef]
70. Tan, Y.; Yu, H.; Li, Y.; Bi, W.; Yao, X. The effect of slag on the properties of magnesium potassium phosphate cement. *Constr. Build. Mater.* **2016**, *126*, 313–320. [CrossRef]
71. Mo, L.; Lv, L.; Deng, M.; Qian, J. Influence of fly ash and metakaolin on the microstructure and compressive strength of magnesium potassium phosphate cement paste. *Cem. Concr. Res.* **2018**, *111*, 116–129. [CrossRef]
72. You, C.; Qian, J.; Qin, J.; Wang, H.; Wang, Q.; Ye, Z. Effect of early hydration temperature on hydration product and strength development of magnesium phosphate cement (MPC). *Cem. Concr. Res.* **2015**, *78*, 179–189. [CrossRef]
73. Qin, J.; Qian, J.; You, C.; Fan, Y.; Li, Z.; Wang, H. Bond behavior and interfacial micro-characteristics of magnesium phosphate cement onto old concrete substrate. *Constr. Build. Mater.* **2018**, *167*, 166–176. [CrossRef]
74. Yang, N.; Shi, C.; Yang, J.; Chang, Y. Research progresses in magnesium phosphate cement—Based materials. *J. Mater. Civ. Eng.* **2014**, *26*, 04014071. [CrossRef]
75. Shi, C.; Yang, J.; Yang, N.; Chang, Y. Effect of waterglass on water stability of potassium magnesium phosphate cement paste. *Cem. Concr. Compos.* **2014**, *53*, 83–87. [CrossRef]
76. Chong, L.; Yang, J.; Shi, C. Effect of curing regime on water resistance of magnesium–potassium phosphate cement. *Constr. Build. Mater.* **2017**, *151*, 43–51. [CrossRef]
77. Ma, H.; Xu, B.; Li, Z. Magnesium potassium phosphate cement paste: Degree of reaction, porosity and pore structure. *Cem. Concr. Res.* **2014**, *65*, 96–104. [CrossRef]
78. Ma, H.; Xu, B.; Liu, J.; Pei, H.; Li, Z. Effects of water content, magnesia-to-phosphate molar ratio and age on pore structure, strength and permeability of magnesium potassium phosphate cement paste. *Mater. Des.* **2014**, *64*, 497–502. [CrossRef]
79. An, P.; Han, Z.; Wang, K.; Cheng, J.; Zhao, Z.; Situmorang, Y.A.; Rizkiana, J.; Abudula, A.; Guan, G. Energy-saving strategy for a transport bed flash calcination process applied to magnesite. *Carbon Resour. Convers.* **2021**, *4*, 122–131. [CrossRef]

80. Del Valle-Zermeño, R.; Formosa, J.; Aparicio, J.A.; Chimenos, J.M. Reutilization of low-grade magnesium oxides for flue gas desulfurization during calcination of natural magnesite: A closed-loop process. *Chem. Eng. J.* **2014**, *254*, 63–72. [CrossRef]
81. Nobre, J.; Ahmed, H.; Bravo, M.; Evangelista, L.; De Brito, J. Magnesia (MgO) Production and Characterization, and Its Influence on the Performance of Cementitious Materials: A Review. *Materials* **2020**, *13*, 4752. [CrossRef] [PubMed]
82. Ravazzolo, F.; Vespignani, J. World steel production: A new monthly indicator of global real economic activity. *Can. J. Econ.* **2020**, *53*, 743–766. [CrossRef]
83. Yellishetty, M.; Mudd, G.M.; Ranjith, P.G.; Tharumarajah, A. Environmental life-cycle comparisons of steel production and recycling: Sustainability issues, problems and prospects. *Environ. Sci. Policy* **2011**, *14*, 650–663. [CrossRef]
84. Musmeci, M.; Rendtorff, N.M.; Musante, L.; Martorello, L.; Galliano, P.; Aglietti, E.F. Characterization of MgO-based tundish working lining materials, microstructure and properties. *Ceram. Int.* **2014**, *40*, 14091–14098. [CrossRef]
85. Pal, A.R.; Bharati, S.; Krishna, N.V.S.; Das, G.C.; Pal, P.G. The effect of sintering behaviour and phase transformations on strength and thermal conductivity of disposable tundish linings with varying compositions. *Ceram. Int.* **2012**, *38*, 3383–3389. [CrossRef]
86. Sahai, Y. Tundish Technology for Casting Clean Steel: A Review. *Met. Mater. Trans. B* **2016**, *47*, 2095–2106. [CrossRef]
87. Liu, Y.; Li, G.; Wang, L.; Zhang, Z. Effect of the Tundish Gunning Materials on the Steel Cleanliness. *High Temp. Mater. Process.* **2018**, *37*, 313–323. [CrossRef]
88. Jha, P.K.; Rao, S.; Dewan, A. Effect of Height and Position of Dams on Inclusion Removal in a Six Strand Tundish. *ISIJ Int.* **2008**, *48*, 154–160. [CrossRef]
89. Mazumdar, D. Review, Analysis, and Modeling of Continuous Casting Tundish Systems. *Steel Res. Int.* **2019**, *90*, 1800279. [CrossRef]
90. Continuous Casting: Find Suppliers, Processes & Material, Manufacturing. Available online: https://www.manufacturingguide.com/en/continuous-casting (accessed on 9 November 2023).
91. Alfocea-Roig, A.; Huete-Hernández, S.; García-Zubiri, X.; Giro-Paloma, J.; Formosa, J. Can tundish deskulling waste be used as a magnesium oxide source to develop magnesium phosphate cement? *J. Environ. Chem. Eng.* **2023**, *11*, 110618. [CrossRef]
92. Quintero-Payan, A.C.; Huete-Hernández, S.; Aguilar-Pozo, V.B.; Astals, S.; Chimenos, J.M. Stabilization of metal and metalloids from contaminated soils using magnesia-based tundish deskulling waste from continuous steel casting. *Chemosphere* **2024**, *348*, 140750. [CrossRef]
93. Lebrouhi, B.E.; Baghi, S.; Lamrani, B.; Schall, E.; Kousksou, T. Critical materials for electrical energy storage: Li-ion batteries. *J. Energy Storage* **2022**, *55*, 105471. [CrossRef]
94. Gielen, D.; Lyons, M. International Renewable Energy Agency, Critical Materials for the Energy Transition: Lithium, Abu Dhabi, United Arab Emirates. 2022. Available online: https://www.irena.org/Technical-Papers/Critical-Materials-For-The-Energy-Transition-Lithium (accessed on 9 November 2023).
95. Dessemond, C.; Lajoie-Leroux, F.; Soucy, G.; Laroche, N.; Magnan, J.F. Spodumene: The lithium market, resources and processes. *Minerals* **2019**, *9*, 334. [CrossRef]
96. Tan, Y.; Yu, H.; Li, Y.; Wu, C.; Dong, J.; Wen, J. Magnesium potassium phosphate cement prepared by the byproduct of magnesium oxide after producing Li_2CO_3 from salt lakes. *Ceram. Int.* **2014**, *40*, 13543–13551. [CrossRef]
97. Wang, H.; Zhong, Y.; Du, B.; Zhao, Y.; Wang, M. Recovery of both magnesium and lithium from high Mg/Li ratio brines using. *Hydrometallurgy* **2018**, *175*, 102–108. [CrossRef]
98. Fuentealba, D.; Flores-Fernández, C.; Troncoso, E.; Estay, H. Technological tendencies for lithium production from salt lake brines: Progress and research gaps to move towards more sustainable processes. *Resour. Policy* **2023**, *83*, 103572. [CrossRef]
99. Ribeiro, D.V.; Paula, G.R.; Morelli, M.R. Use of microwave oven in the calcination of MgO and effect on the properties of magnesium phosphate cement. *Constr. Build. Mater.* **2019**, *198*, 619–628. [CrossRef]
100. Zheng, W.; Dong, J.; Wen, J.; Chang, C.; Xiao, X. Effects of water-to-cement ratios on the properties of magnesium potassium phosphate cement prepared with lithium-extracted magnesium residue. *Appl. Sci.* **2021**, *11*, 4193. [CrossRef]
101. Liu, P.; Dong, J.; Chang, C.; Zheng, W.; Liu, X.; Xiao, X.; Wen, J. Preparation of low-cost magnesium oxychloride cement using magnesium residue byproducts from the production of lithium carbonate from salt lakes. *Materials* **2021**, *14*, 3899. [CrossRef]
102. Luza, A.L.; Simão, L.; Acordi, J.; Raupp-Pereira, F.; Innocentini, M.D.M.; Montedo, O.R.K. Synthesis of chemically bonded porous ceramics from MgO–C refractory bricks waste. *Ceram. Int.* **2022**, *48*, 3426–3434. [CrossRef]
103. Nanda, S.; Choudhury, A.; Chandra, K.S.; Sarkar, D. Raw materials, microstructure, and properties of MgO–C refractories: Directions for refractory recipe development. *J. Eur. Ceram. Soc.* **2023**, *43*, 14–36. [CrossRef]
104. Wang, X.; Li, X.; Lian, L.; Jia, X.; Qian, J. Recycling of waste magnesia refractory brick powder in preparing magnesium phosphate cement mortar: Hydration activity, mechanical properties and long-term performance. *Constr. Build. Mater.* **2023**, *402*, 133019. [CrossRef]
105. Dai, X.b.; Lian, L.; Jia, X.-w.; Qin, J.-h.; Qian, J.-s. Preparation and properties of magnesium phosphate cement with recycled magnesia from waste magnesia refractory bricks. *J. Build. Eng.* **2022**, *63*, 105491. [CrossRef]

106. Sinha, S.; Ghosh, S.; Samanta, A.K. Influence of waste refractory brick on the destructive and non-destructive properties of sustainable eco-friendly concrete. *Mater. Today Proc.* **2023**, *in press*. [CrossRef]
107. Andrew, R.M. Global CO_2 emissions from cement production, 1928–2018. *Earth Syst. Sci. Data* **2019**, *11*, 1675–1710. [CrossRef]
108. Habert, G.; Miller, S.A.; John, V.M.; Provis, J.L.; Favier, A.; Horvath, A.; Scrivener, K.L. Environmental impacts and decarbonization strategies in the cement and concrete industries. *Nat. Rev. Earth Environ.* **2020**, *1*, 559–573. [CrossRef]
109. Dorozhkin, S.V. Calcium orthophosphate cements for biomedical application. *J. Mater. Sci.* **2010**, *45*, 4441–4467. [CrossRef]
110. Lazorenko, G.; Kasprzhitskii, A. A review of magnesium-rich wastes and by-products as precursors for magnesium phosphate cements: Challenges and opportunities. *Environ. Res.* **2025**, *285*, 122402. [CrossRef]