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Sustainable Progress Based on the Current Situation of Global Cement Production

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Abstract. The construction industry is a major source of global carbon emissions, particularly the environmental impact of cement production. Starting with global environmental issues, this paper expounds the current situation of carbon emissions in the building materials industry, especially cement production. This paper quantitatively analyzes the sources of carbon emissions in the cement production process, including the stages of raw material mining, clinker calcination, mixing and grinding. Based on existing research and data, this paper reveals the future of cement production from manufacturing techniques and raw materials. Green manufacturing techniques (e.g. alternative fuel (AF) technology, carbon capture and storage technology), and the application of low-carbon substitutes materials (e.g. pozzolan and fly ash) are highlighted. The research shows the development of green manufacturing techniques and low-carbon substitutes is essential for the sustainable development of the cement industry. Through these studies, promising manufacturing techniques and cement substitutes have been identified to provide constructive solutions for achieving global carbon reduction targets.

Keywords: Cement production; Carbon emissions; Green manufacturing techniques; Low-carbon substitutes.

1. Introduction

With the rapid development of the global economy, the urbanization is accelerating, and the number of infrastructure construction is growing. As one of the most important building materials, the demand for cement has also risen. However, the manufacturing of cement is highly associated with processes with high energy consumption and high emissions [1]. This situation has aroused widespread environmental concerns, prompting researchers to explore how to reduce the carbon emission level and achieve sustainable development while satisfying the normal production of cement. Therefore, studying the carbon emissions in the life cycle of cement production and finding effective emission reduction strategies have become important topics for global response to climate change and environmental protection [2].

It is of great theoretical and practical significance to study the carbon emission problem in the cement manufacturing process. From a theoretical point of view, the analysis of carbon emissions in all stages of cement production (such as raw material acquisition, preparation and production, construction and use, waste disposal) can provide important data support for the scientific assessment of the environmental impact of the cement industry. At the same time, it will enrich the theoretical system of low-carbon economics. From the perspective of practical application, the research results of cement carbon emissions can provide a reference for policymakers and help them formulate more reasonable emission reduction policies. In addition, these low-carbon techniques and management strategies proposed by the research can guide enterprises to improve energy efficiency and reduce production costs. According to these theories, people can optimize production processes and enhance their competitiveness [3]. Therefore, carrying out research on sustainable progress based on the current situation of cement production in the world will not only help promote the green transformation of the cement industry, but also be one of the important ways to achieve the global carbon neutrality goal.

At present, there have been many studies on carbon emissions in the cement industry around the world. From the perspective of research themes, it mainly focuses on the following aspects: First, the research on green cement production technology, such as alternative fuel (AF) technology, new suspension preheater (NSP) rotary kiln technology, carbon capture and storage (CCS) technology, etc. Second, the research on low-carbon cement substitutes, such as replacing some cement clinker with industrial by-products (e.g. fly ash, steel slag). Although some progress has been made in some fields, most of the existing studies focus on the analysis of specific stages or technologies. Also, there is a lack of systematic research on the carbon emissions of cement throughout its life cycle. In addition, the variation of resources, technologies, and policies in different regions of the world also affect the performance and potential of carbon emissions, so more comprehensive research based on global perspectives is needed [4].

2. Current Situation and Challenges of Cement Production

2.1. Current Situation of World Cement Production

According to statistics, global cement production has increased from less than 200 million tons in the 1950s to about 4.2 billion tons in 2023. Asian is a major region for cement production, especially in China and India. They account for more than 60% of total global production. Among them, China's economy has developed rapidly since the 1980s, becoming the world's largest cement producer and consumer, accounting for more than 50% of the world's total output [5].

Global cement production presents several distinct characteristics. First, since the global economy slowed down in recent years, the growth rate of cement production has also declined [6]. Fig.1 shows that China's cement production peaked in 2020 and began to decline gradually. This trend is partly due to the structural transformation of the domestic economy and the government's increasing environmental requirements, including the measures such as eliminating outdated technologies and limiting new cement plants' establishment. Second, although cement demand in developed countries has stabilized or even decreased, cement demand in emerging markets such as India, Southeast Asia, the Middle East and Africa remains strong. Especially in India and Vietnam, accelerating urbanization and strong demand for infrastructure construction have contributed to the continued growth of global cement production [7]. Finally, the cement industry is under pressure to transition to sustainability as global concerns about carbon emissions and climate change increase. More and more companies are investing in low-carbon cement, the use of alternative raw materials and fuels, and CCS technology to reduce carbon emissions in the manufacturing process.

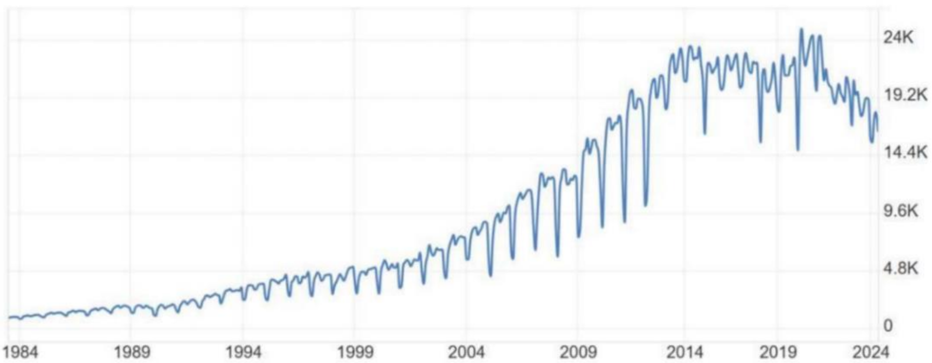

Figure 1. Cement production in China from 1984 to 2024 [6]

2.2. Challenges of World Cement Production

Concrete industry is one of the basic pillars of the construction industry. Of all the building materials, concrete has the lowest embodied energy and is produced on the largest scale. Cement, as one of the main components of concrete, produces a total of 4.2 billion tons per year. For every ton of cement clinker, 0.9 tons of CO_2 is produced. According to the data from International Energy Agency (IEA), the cement industry contributes about 8% of the world's total carbon emissions, becoming one of the main sources of global greenhouse gas emissions [8].

The carbon dioxide produced in the manufacturing process of cement clinkers mainly comes from the following three aspects: fuel emissions, process emissions, and indirect emissions. The first two belong to the type of direct emissions. Fuel emission refers to the CO_2 released by the combustion of the fuel when heating the kiln to calcinate the raw material. This accounts for about 40% of direct CO_2 emissions. The process emissions are the CO_2 released from raw materials such as limestone minerals during calcination, accounting for about 50% of the direct CO_2 emissions. Indirect CO_2 emissions are related to the electricity consumed in cement production, accounting for less than 10% of total CO_2 emissions [5, 9]. From the proportion of CO_2 emissions at each stage of cement production, it is necessary to reduce fuel emissions and process emissions from the process and raw material aspects respectively. Therefore, the impact of greenhouse gases would significant reduced,

3. Green Manufacturing Techniques of Cement

Calcination and kiln systems are the main sources of carbon emissions in cement production. To reduce carbon emissions in these processes and improve the cement manufacturing techniques (CMT), it is important to develop and apply various green technologies and methods. Here are a few green technologies related to cement calcination and kilns.

3.1. AF Technology

In cement production, rotary kilns for calcined limestone need to be burned at high temperatures. It has a huge requirement for fuel. Portland cement (PC) production is dominated by traditional fuels such as coal and oil, yet the combustion of fossil fuels leads to significant CO_2 and gaseous pollutant emissions. To reduce environmental impact and conserve resources, the use of AF technology is the most straightforward form of CMT. AFs are generally divided into waste fuels and biofuels [10].

Waste fuels include municipal solid waste, waste tires, plastics, etc., which generally have a high calorific value and can be used as a replacement for fossil fuels. However, it is important to note that the combustion process of waste fuels is extremely complex and can produce many toxic gases. Therefore, reasonable control and harmless treatment have become the biggest restrictions on the replacement of fossil fuels with waste fuels [11]. Biofuel is another important source of AFs, including waste wood, textiles and paper residues, etc. Biofuels are considered carbon neutral because the CO_2 absorbed by living organisms as they grow also enters the atmosphere after death. Therefore, the CO_2 produced when burning biofuels can be regarded as a normal carbon cycle process in natural [12, 13].

In addition to the alternative energy sources mentioned above, hydrogen also helps to reduce CO_2 emissions in the cement industry. When pure hydrogen is used as fuel, the product is only water without any carbon emissions. Moreover, due to the better ignition characteristics and higher calorific value of hydrogen, the heat transfer efficiency will be improved, and energy loss will be reduced. However, the lack of availability and affordability of hydrogen fuel in most cement plants has limited the popularity of such an efficient alternative energy source so far [13]. It is believed that in the future, when hydrogen fuel becomes more accessible and cost-effective, hydrogen fuel will replace fossil fuels as they are today.

3.2. CCS Technology

CCS is one of the key technologies to reduce carbon dioxide emissions in cement production. CCS reduces carbon emissions by capturing, transporting, and sequestering carbon dioxide to permanently sequester it out of the atmosphere. CCS is one of the few carbon emission treatment technologies suitable for heavy industry, because the CO_2 from cement production is mainly due to chemical reactions and fuel emissions. The carbon dioxide produced is concentrated and abundant, which is very suitable for CCS unified treatment [14].

Carbon capture is the first step in CCS and includes adsorption, oxyfuel technology, calcium-looping, membrane technology. Adsorption technology, also known as chemical absorption, typically uses ethanolamine solvents to capture carbon dioxide in flue gases [15]. This method is suitable for the environment of low pressure and low concentration CO_2 in large cement plants, and the capture efficiency is high. Oxyfuel technology is a method of combustion by injecting pure oxygen into the kiln instead of air [16]. The resulting flue gas has a higher CO_2 concentration, which makes the subsequent capture process more efficient. The calcium-looping is based on the technology of calcium oxide adsorbents to capture carbon dioxide from flue gases, and its core involves two basic reactions.

$$\mathrm{CaO} + \mathrm{CO_2} = \mathrm{CaCO_3} \quad (1)$$

$$\mathrm{CaCO_3} = \mathrm{CaO} + \mathrm{CO_2} \quad (2)$$

This cycle can be carried out continuously and is suitable for flue gas treatment with high CO_2 levels. Calcium oxide can be reused many times to become a cyclic process of capturing carbon dioxide [17]. Membrane separation technology uses selective breathable membrane materials to effectively separate flue gases as they pass through the membrane. Despite the simplicity of operation, membrane units can only be used on a small scale. Additionally, the membrane is sensitive to some trace elements and is not resistant to high temperatures. The durability and cost of membrane materials need to be further developed [18].

CCS technology also faces some challenges, such as the need for significant government investment in the infrastructure responsible for carbon transport, and the choice of carbon sequestration sites to ensure long-term security. With technological advancements and the cement industry driving the economy, the economic viability of CCS is expected to increase [19].

3.3. NSP Rotary Kiln Technology

When it comes to the NSP rotary kiln, the center of this technology is the efficient preheating of the cement raw material through the suspension preheater system. The raw material will decompose inside the calciner and then enter the rotary kiln to complete the calcining process. The NSP rotary kiln system consists of a preheater, a calciner, a rotary kiln and a cooler [20]. Compared to traditional shaft kiln systems, the energy efficiency is significantly improved because the preheating of the clinker and the decomposition of the carbonate are carried out in separate preheaters and calciners. At the same time, the length of the rotary kiln is also greatly shortened, resulting in the acceleration of heat transfer between the gas and the solid, and the reduction of losses [21].

Based on the complete equipment system, the NSP rotary kiln technology has a high degree of automation. The capacity of the system to calcine raw materials in suspension is enhanced, which efficiently meets the production needs of large cement plants. However, the NSP rotary kiln system involves a multi-stage preheater and a large calciner, and the initial investment is high, which is a challenge especially for small and medium-sized enterprises [22]. The more complex and sophisticated system also means that NSP rotary kilns can be combined with carbon capture, AFs and other technologies to further improve the sustainability and competitiveness of cement production. It provides a comprehensive solution to the carbon neutrality of the cement industry.

4. Sustainable Substitutes of Cement

Modern concrete and cement manufacturing processes typically involve life cycle assessment (LCA). Most life cycle inventory analyses focus on greenhouse gas emissions and global warming potential (GWP). It often ignores the impact of pollutants and toxic substance emissions [23]. Traditional PC manufacturing has a significant environmental impact but using various cement substitutes can help reduce this impact and improve the recycling rate of industrial waste. Cement substitutes generally refer to materials that have similar functional properties to PC or can partially replace its components. These materials have lower carbon emissions while meeting the physical performance requirements of construction [24].

4.1. Pozzolan

Pozzolan is a composite material containing silica and alumina in the form of finely crushed particles. When natural pozzolan is present on its own, it does not have cementitious property. However, these compounds can react with hydrated lime in water to obtain cementitious property [13, 25]. The specific pozzolan reaction is:

$$A_xS_y + mCH + nH = C - S - H + C - A - H \tag{3}$$

The resulting secondary cementitious material (SCM) can replace 40% of conventional cement to fill the gaps in the concrete, thereby improving the mechanical properties and durability of the concrete [24].

There are three benefits to replacing the role of PC in concrete with pozzolan: First, natural pozzolan is extremely abundant in some areas, and it does not require a lot of energy and cost to harvest these raw materials. Therefore, it is economically beneficial for natural pozzolan to replace PC. Secondly, it can be seen from the reaction formula that the pozzolan reacts with $Ca(OH)_2$ to form calcium silicate hydrate (C-S-H) and calcium aluminate (C-A-H). It effectively reduces the content of calcium carbonate in PC and reduces greenhouse gas emissions. Finally, due to the activity of pozzolan, its initial strength is lower than that of PC. But a finer pozzolana fill means a denser binder, so pozzolana concrete also has a higher compressive strength. In addition, the activity of pozzolan results in better corrosion resistance to aggressive liquids, so pozzolan improves the durability of concrete [25].

4.2. Fly Ash

Fly ash is a coal combustion residue that accounts for about 80% of coal combustion by-products. Fly ash is currently the most used substitute for PC clinker in the world, and it can also be used as SCM. The composition of fly ash from different sources is quite different, but all of them contain a large amount of SiO_2, Al_2O_3 and CaO [26]. Its properties are like those of natural Pozzolans, so it is also known as man-made Pozzolans. Before the Pozzolans reaction occurs, the fly ash is added with water and then the one-step hydration reaction is carried out:

$$CaO + H_2O = Ca(OH)_2 \tag{4}$$

Finally, cement compounds C-S-H and C-A-H can still be formed, thereby improving concrete properties.

The main reason why fly ash can be widely used in cement substitution is that it can significantly reduce environmental pollution and solve the problem of subsequent treatment of related industrial waste. More than 750 million tons of fly ash are produced from coal-fired power plants every year, and most of the waste is generally disposed of in landfills, but fly ash contains trace amounts of heavy metal elements that are toxic to living organisms, and if they are directly treated, they will directly leach out polluted soil and water sources, and finally accumulate in the human body [27]. The use of fly ash as a cement substitute in concrete not only eliminates the need for CO_2 from the additional manufacture of PC, but also recycles coal combustion by-products, reducing the cost of concrete production and the cost of disposing of pollutants.

4.3. Steel Slag

Steel slag, also known as blast furnace slag (BFS), is a by-product of the ironmaking and metal recovery process. With the rapid development of the steel industry, the output of steel slag has increased year by year. As a result, finding ways to utilize this excess slag to reduce its environmental impact has become a problem. Steel slag has several properties that make it have excellent properties comparable to cement in the construction sector. For example, steel slag has the properties of being hard and wear-resistant, so it can be added to concrete as an aggregate for added strength. In addition, the cementitious properties of BFS allow it to be combined with cement to produce "slag cement" that is more economical than PC [28].

What's more, slag cement can be recycled as a by-product, bringing China's two major industries together. As shown in Fig. 2, the process is: BFS is produced when iron ore is converted into molten pig iron in a blast furnace at about 1600°C. Subsequently, the BFS can be quickly cooled with a large amount of high-pressure steam, resulting in granular slag. After processes such as pretreatment, the slag can be converted into slag cement, which can then be used with steel bars produced by the steel industry to make reinforced concrete [29]. This approach maximizes resource utilization between the two main industries, significantly reduces costs, and protects the environment.

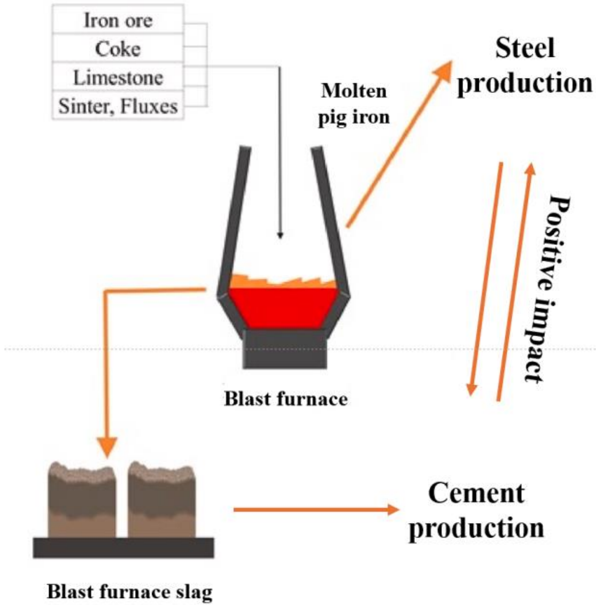

Figure 2. The relationship between steel slag cement production and steel industry [29]

4.4. Rice Husk Ash (RHA)

RHA is a by-product obtained from agriculture and contains a large amount of amorphous active silica. As SCM can be used to improve the production of PC to form High Performance Concrete (HPC). RHA can be used as a fine aggregate in concrete pouring with cement, where fine silica particles can form a denser concrete. At the same time, the fineness of RHA allows it to penetrate deeper than conventional cement mixtures, leaving smaller pores to act as insulation [30].

More than half of the world's population depends on rice as a staple food, and about 22% of the weight of a rice is made up of husks. After combustion, 25% of the weight of the husk is converted into RHA [31]. Replacing cement with RHA in concrete will not only reduce reliance on PC, but also improve the mechanics and durability of concrete [32]. More importantly, this cement substitute successfully combines agriculture and industry, which not only reduces the production cost of concrete, but also solves the problem of the utilization of RHA and reduces the waste of resources.

5. Conclusion

This paper analyzes the current situation of global cement production and its carbon emissions and discusses how to achieve green and sustainable development while maintaining cement production efficiency. Combined with the issue of carbon emissions in the cement production process, as well as the listed cement production technologies and cement alternatives. In view of the future development trend of the cement industry, the following two conclusions can be drawn:

(1) Green production technology will become the mainstream of the cement industry in the future. AF technology and CCS technology are the focus of current research and practice. AF technologies can both reduce carbon emissions and contribute to resource recycling by replacing traditional fossil fuels with waste and biomass fuels. At the same time, with the gradual popularization of hydrogen energy, the use of hydrogen instead of traditional fuels in the future will also significantly reduce carbon emissions in the cement production process. CCS technology provides an effective way to reduce carbon emissions by capturing and sequestering carbon dioxide, although the technology needs to be further refined in terms of economic viability.

(2) The development of low-carbon cement alternatives will become an important driving force for the sustainable development of the cement industry. Alternative materials such as pozzolan, fly ash, steel slag, and RHA can not only reduce the use of traditional cement, but also improve the strength and durability of concrete, and reduce environmental pollution. These alternatives are expected to complement traditional cement in the future and promote the green transformation of the building materials industry.

In summary, technological progress and policy support will work together to promote the green transformation of the cement industry. With the gradual improvement of environmental protection policies and increasingly strict control of carbon emissions, cement companies will face more challenges and opportunities. In the future, the cement industry needs to work together with the government, enterprises and scientific research institutions to achieve an efficient and low-carbon production model through technological innovation and management optimization, and ultimately achieve sustainable development goals. The future of the cement industry will be green and low-carbon, and the application of new technologies and the promotion of low-carbon alternatives will make a positive contribution to the realization of the global carbon neutrality goal.

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