Carbon Dioxide Storage Technology in Cement Materials for Addressing Global Warming

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Abstract. Recently, global warming is one of the most environmental problems for people to sovle it. As occupied 6% of the global emissions of the greenhouse gases. the cement industry needs largely carbon reduction. With this situation, Carbon Capture Utilization&Storage (CCU&CCS) technology emerges as a benefit method. It can reduce the CO_2 emission from the cement industry by capture it. The mechanism of the carbon capture in cement has two main types: chemical and physical. And two mechanisms can also work together to produce a synergistic effect. The products of this reaction can also enhance cement strength. There are also two types of cement used in this technology: Traditional cement and modified cement. They can used in different cases with the different costs and effects. In addition, the cost of the technology now is quite expensive but one part of the process-mainstream processes-may fall in the future with the advancement of process. This technology is vital for the cement industry's carbon neutrality and global warming.

Keywords: Global warming; cement; carbon neutrality; carbon dioxide; carbon capture.

1. Introduction

As one of the most severe environmental issue in the world today, global warming's main cause may attributes to the carbon dioxide (CO_2) emissions [1]. More than 80% of energy, like the electricity, is generated from fossil fuel in the word. And in those production, more than 24 billion tons of CO_2 have been polluted [2]. And the largest part of it belongs to the industrial sector-the carbon emission of it is around 27% of total CO_2 emissions [3]. In the industrial sector, the cement industry has emitted second large industrial emission source-it emitted 6% of global greenhouse gas-just behind the steel industry [4]. In the production of cement, every kilogram(kg) of cement manufactured results 0.5 to 0.7 kilograms of CO_2 emission [1].

Fortunately, Carbon Capture Utilization and Storage technology has become a vital tool to reduce global warming by reducing the amount of CO_2 emission. The significance of CCUS technology to solve global warming is-it can led industries to continue using fossil fuels while cutting down or eliminating their CO_2 emissions [3]. It can capture CO_2 from industrial emission sources, then change it to some useful sources, if not, it can also just storing it safely. As the expert said, carbon capture may have the greatest potential for reducing CO_2 emissions among all mitigation technologies [5]. For the cement industry, CCUS technology can not only limit CO_2 emissions when cement is produced, but also can improve the performance of the cement.

This paper is talking about the types of the cement can use CCUS technology, it's mechanisms, process, and application. By organizing existing research findings, it explains the key technologies employed to achieve CO_2 storage in cement-based materials, conducts in-depth analysis of the underlying chemical and physical mechanisms, and examines how these technologies are currently applied in real-world scenarios. The ultimate aim is to provide engineering-based solutions for addressing global warming and promote the application and popularization of this technology.

2. Core Mechanisms of CO_2 Storage in Cement-Based Materials

Two main mechanisms govern CO_2 storage in cement materials: chemical and physical mechanisms. These two mechanisms can operate together, and form a synergistic effect, collectively

determining the total amount, rate, and stability of carbon storage. Together, they make a rudimentary explanation for the feasibility of this technology in engineering applications.

2.1. Chemical Storage Mechanism

The key to chemically storing CO_2 in cement-based materials is the carbonation reaction between CO_2 and cement hydration products. During cement hydration, calcium hydroxide ($Ca(OH)_2$) and complex calcium-silicate-hydrate (C-S-H) gel are produced, though latter will not be the focus of discussion in this paper. Stable calcium carbonate ($CaCO_3$) is formed when CO_2 reacts with $Ca(OH)_2$, and the corresponding chemical equation is as follows [2]:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O \quad (1)$$

Meanwhile, CO_2 also reacts with calcium ions in the C-S-H gel, leading to the further formation of carbonate products like $CaCO_3$. This reaction process alters the chemical composition of cement-based materials, converting gaseous CO_2 into solid carbonates and thus fixing CO_2 in cement-based materials in a solid form.

Several factors cause a significant influence on the rate of the carbonation reaction, including temperature, humidity, and CO_2 concentration. Generally speaking, higher temperatures speed up molecular movement, which in turn enhances the reaction rate between CO_2 and cement hydration products. Humidity is also critical: an appropriate amount of moisture acts as a reaction medium, accelerating ion transport and reaction progress. However, excessively high humidity is detrimental to the reaction; instead, it may impede the reaction. A higher CO_2 concentration usually leads to a faster reaction rate, as high-concentration CO_2 provides an ample supply of reactants, driving the reaction forward. Nevertheless, once the CO_2 concentration reaches a certain threshold, the upward trend of the reaction rate may gradually slowdown.

2.2. Physical Storage Mechanism

Cement-based materials have a complex pore structure. CO_2 molecules can be adsorbed on the surface of these pores and fills the interior of the pores. This physical storage method is closely tied to the porosity and pore size distribution of cement-based materials. It seems for Cement-based materials with higher porosity and suitable pore sizes to have more space for the physical storage of CO_2, but there is no relative research yet.

In addition, the inter-molecular forces (IMFs) between CO_2 and the microstructure of cement may also increase the physical CO_2 storage. CO_2 molecules may form weak chemical bonds or van der Waals forces with atoms or molecules on the pore surface, which enhances the stability of their adsorption on the pore surface.

2.3. Synergistic Storage Effect

In reality, the chemical and physical storage mechanisms is very likely to work together and improve the efficiency. By physical storage, the adsorption of CO_2 in pores can increase the contact between CO_2 and cement, thereby promoting the chemical reaction rate since the contact area is a major factor affecting the reaction rate. This synergistic effect can increase the overall CO_2 storage efficiency.

2.4. Structural Performance Optimization of Stored Products

In the reaction of CO_2 and cement, products like $CaCO_3$ can have a positive impact on the strength of the cement. When it fills the pores, it can enhance the material's compressive strength-make it harder to compress since there is no space inside. And also, $CaCO_3$ improves the impermeability of the cement, and reducing the intrusion of some harmful materials that can led cement damage.

And also, some issues such as shrinkage and cracking may decrease cement structural performance and service life. However, by using those carbon storage process, cement's stability can

be improved. $CaCO_3$-the products in the reaction-can fills some pores, reducing volume shrinkage problems caused by factors like moisture evaporation. This lower the risk of shrinkage cracking.

3. Cement Material Systems Suitable for CO_2 Storage

Cement material systems suitable for CO_2 storage have two main categories: traditional cement materials and modified cement materials. Their storage capacity and engineering adaptability can be determined by their properties such as hydration characteristics, mineral composition, and structural innovation. They provide options for the application of CO_2 storage technology in the cement industry.

3.1. Traditional Cement Materials

Traditional cement materials are the basic carriers for CO_2 storage. Their storage capacity is related to their characteristics and mineral composition.

3.1.1 Portland Cement

Portland cement is the most widely used type of cement in the world. Its CO_2 storage capacity is directly linked to the one if it process stage--hydration stage. During the hydration, $Ca(OH)_2$ and C-S-H gel are produced. In the early hydration stage, the production of $Ca(OH)_2$ increases gradually, and provide a sufficient reaction for CO_2. In the middle and late hydration stages, the C-S-H gel further participates in the reaction. It can increase the formation of the $CaCO_3$ like as mentioned earlier, which increase in the total amount of carbon storage [1].

3.1.2 Aluminate Cement

Aluminate cement has the unique advantage in the CO_2 storage process: it can rapid carbonation. Its main mineral components have a fast hydration rate, but the specific reasons will not be discussed here. This characteristic makes it suitable for some tight construction schedules. In factory production, aluminate cement components can complete carbonation in 24 hours. This ability can be used to achieves rapid CO_2 storage, which will definitely shortens the production cycle [1].

3.2. Modified Cement Materials

Some modified cement materials have become the focus of development because it can enhance the CO_2 storage performance. The main idea of this is to enhance reactivity with CO_2 through composition and structure [6].

3.2.1 Blended Cement

By incorporating industrial by-products such as slag, fly ash, and silica fume, the CO_2 storage performance of blended cement can be significantly optimized. On one hand, the reactive SiO_2 and Al_2O_3 contained in these by-products can react with cement hydration products to generate more substances that can participate in carbonation. On the other hand, the addition of industrial by-products can reduce the amount of cement clinker used, which directly reduces emissions generated from limestone calcination during cement production [1].

3.2.2 Alkali-Activated Cement

As a clinker-free cement, its production does not require high-temperature calcination—its carbon footprint is only 1/3 to 1/2 that of Portland cement—and it also exhibits high reactivity. Alkali-activated cement is prepared using industrial waste residues (such as steel slag and fly ash) and alkali activators (such as NaOH and water glass). Its gel system contains a large number of reactive calcium and aluminum ions, which can react rapidly with CO_2 to form carbonates and stable gel products—its CO_2 storage efficiency is significantly higher than that of traditional Portland cement [1].

4. Process Paths and Cost Analysis of CO_2 Storage Technology

The CO_2 storage technology has two key dimensions: mainstream process technologies and cost composition. Mainstream processes differ significantly in principles, maturity, and costs, while cost analysis covers direct expenses and economic comparisons with geological storage. These contents jointly provide technical feasibility references for CO_2 storage technology.

4.1. Mainstream Process Technologies

Currently, a variety of processes exist for CO_2 storage in cement-based materials, including amine scrubbing, oxy-fuel combustion, calcium looping, and direct separation [4]. These technical methods differ in terms of principles, efficiency, energy requirements, and costs. For example, amine scrubbing and oxy-fuel combustion are relatively mature technologies and have been applied in some Carbon Capture and Storage (CCS) projects, but they are associated with extremely high costs. There are also other technologies that may have low costs but lack clear pathways for large-scale application. Given this, it is essential to conduct a comprehensive evaluation of the advantages and disadvantages of each technology and carry out in-depth analysis. Furthermore, since most of the technologies discussed in this paper are still in the research and development stage, even for the same technology, there are obvious differences in the descriptions of various technical and economic indicators in the literature.

4.2. Cost Composition and Economic Analysis

The cost of CO_2 storage technology comprises direct costs and indirect costs.

4.2.1 Direct Costs

Direct costs mainly consist of three parts: CO_2 capture (for instance, in industrial flue gas purification—when it comes to amine scrubbing technology, the cost stands at roughly 60–80 USD per ton of CO_2, while calcium looping technology costs about 40–60 USD per ton of CO_2), transportation (pipeline transportation costs around 2–5 USD per ton of CO_2, and tank truck transportation costs approximately 10–15 USD per ton of CO_2), and injection processes (including equipment depreciation and energy consumption, totaling about 5–10 USD per ton of CO_2). Among these, carbon capture is the core cost driver—due to the low CO_2 concentration in cement kiln flue gas (around 10%–15%), the difficulty of purification is higher than that of flue gas from power plants. Although the current cost of CCUS is relatively high (approximately 100–150 USD per ton of CO_2) , it is expected to decrease significantly in the future with technological progress and the deployment of large-scale projects [7].

4.2.2 Economic Comparison

Compared with geological storage, cement-based storage has the advantage of not requiring long-term monitoring (geological storage requires monitoring for 50–100 years, with a cost of approximately 5–10 USD per ton of CO_2) and allowing for the recycling and utilization of products. However, it also has a drawback: its unit storage capacity is relatively low (cement-based storage can store about 50–100 kg of CO_2 per ton of material, while geological storage can reach tens of thousands of tons of CO_2 per well).

5. Practical Application Cases and Engineering Practices

A number of pilot projects at home and abroad have verified the feasibility of CO_2 storage technology, providing references for large-scale promotion.

5.1. International Cases

The Longship project is a CCS project implemented at two industrial sites in Norway. This project captures CO_2 and stores it permanently in an offshore reservoir. As the first CCS project

covering the entire CCUS value chain, it has a total CO_2 capture capacity of 800,000 tons, with emissions coming respectively from the Norcem cement plant in Brevik and the Hafslund Oslo Celsio waste incineration plant in Oslo. The Norcem cement plant in Brevik will adopt post-combustion capture technology (amine scrubbing), with technical support provided by Aker Carbon Capture. [8].

5.2. Domestic Cases

China Resources Cement has constructed a CCUS pilot project in Guangdong, focusing on factory-based carbonation curing of precast concrete piles. This project achieves an annual CO_2 storage of approximately 5,000 tons, increases the compressive strength of the piles by 20%. China National Building Material Group has implemented a recycled aggregate carbonation project in Anhui, where recycled aggregates from waste concrete undergo carbonation treatment before being used in concrete production. This project utilizes 100,000 tons of solid waste annually, stores approximately 500 tons of CO_2 [7].

6. Conclusion

In summary, with the global warming, the cement industry need to mitigating a lot carbon for solving climate issues. CCUS technology not only reduces carbon emissions during cement production, but also optimizes the performance of the cement.

From the perspective of mechanisms, CO_2 storage in cement-based materials relies on the both chemical and physical mechanisms. Chemically, CO_2 undergoes a reaction with cement hydration products to form stable $CaCO_3$. Physically, CO_2 adsorption and filling are achieved through the pore structure of cement-based materials. These two mechanisms work together to enhance the total storage amount and stability.

In terms of materials, traditional Portland cement and aluminate cement serve as basic carriers for storage. Modified and new-type cement materials further enhance storage performance through composition optimization and structural innovation.

In terms of process paths, mainstream technologies have their own advantages and disadvantages. The current cost with carbon capture as the core cost component—but costs are expected to decrease in the future with the large-scale application of the technology. Compared with geological storage, cement-based storage does not require long-term monitoring, although its unit storage capacity is relatively low.

Practical applications at home and abroad have verified the feasibility of the technology, further confirming the engineering adaptability of CO_2 storage technology in cement materials.

In the future, continuous efforts should be focused on material modification and process innovation to promote its large-scale application, supporting the cement industry in achieving carbon reduction goals and providing practical engineering solutions for global efforts to address global warming.

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