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COMMENTARY

Carbon utilization in construction materials: Technologies, challenges, and opportunities

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INTRODUCTION

Climate change, driven by rising carbon dioxide (CO_2) levels and the resulting greenhouse effect, stands as one of the most pressing environmental challenges of our time. The construction industry faces unprecedented pressure in this crisis, yet it also holds unique opportunities for transformation. According to the 6th Assessment Report by the United Nations' Intergovernmental Panel on Climate Change, the global average surface temperature has already risen by approximately 1°C compared to pre-industrial levels. Without substantial decarbonization measures, temperatures could exceed 1.5°C within the next two decades, approaching the critical threshold of 2°C. While carbon capture, utilization, and storage (CCUS) technologies have gained prominence in energy and industrial sectors, their application in construction materials remains underdeveloped. This is particularly concerning, as the construction industry contributes 39% of global energy-related CO_2 emissions and consumes 36% of the world's total energy.[1]

The construction materials sector, particularly in cement and lime production, relies heavily on carbonate minerals as raw materials. Emissions from this sector account for approximately 11% of the construction industry's total carbon footprint, as illustrated in Figure 1. An analysis of cement production emissions reveals that approximately 62% of CO_2 comes from the decomposition of carbonate minerals and 33% of CO_2 from fuel combustion.[2] This distinctive emission leads the cement industry apart from sectors like steel and power, where fuel combustion dominates carbon output. Even with the complete elimination of fossil fuel use, achieving carbon neutrality in cement production remains challenging due to process-related emissions. Consequently, CCUS technologies have emerged as a critical backstop solution for decarbonizing the construction industry.

This commentary explores the potential of carbon utilization technologies to transform the construction industry from a significant carbon source into a viable carbon sink. It also evaluates their feasibility in addressing the growing global demand for sustainable infrastructure. Furthermore, it highlights the critical role of policy support, market incentives, and industry collaboration in accelerating these solutions.

TECHNOLOGIES FOR CARBON UTILIZATION IN CONSTRUCTION MATERIALS

CO_2 resource utilization addresses the dual challenges of carbon storage and environmentally friendly material production. Concrete, for instance, chemically interacts with atmospheric CO_2 throughout its lifecycle. These reactions primarily involve the interaction of CO_2 with cement hydration products – calcium hydroxide ($Ca(OH)_2$), calcium silicate hydrate (C-S-H), and calcium aluminate hydrate (C-A-H) – ultimately forming stable carbonate minerals such as calcium carbonate ($CaCO_3$). Concrete carbonation can be broadly categorized into two main types: weathering carbonation (e.g., natural carbonation) and active carbonation (e.g., accelerated carbonation).

Weathering carbonation, or passive carbonation, occurs on the surface of hardened concrete at a relatively slow rate. Over its long service life, atmospheric CO_2 diffuses through the multi-scale pore network of the concrete, reaching internal voids where it reacts with liquid and solid phases. This process converts atmospheric CO_2 into stable carbonate minerals, sequestering CO_2 within the structure and enhancing the material's engineering performance. Active carbonation represents a proactive approach to CO_2 utilization, shifting from passive atmospheric carbonation to controlled CO_2 incorporation. This process typically occurs in controlled environments and

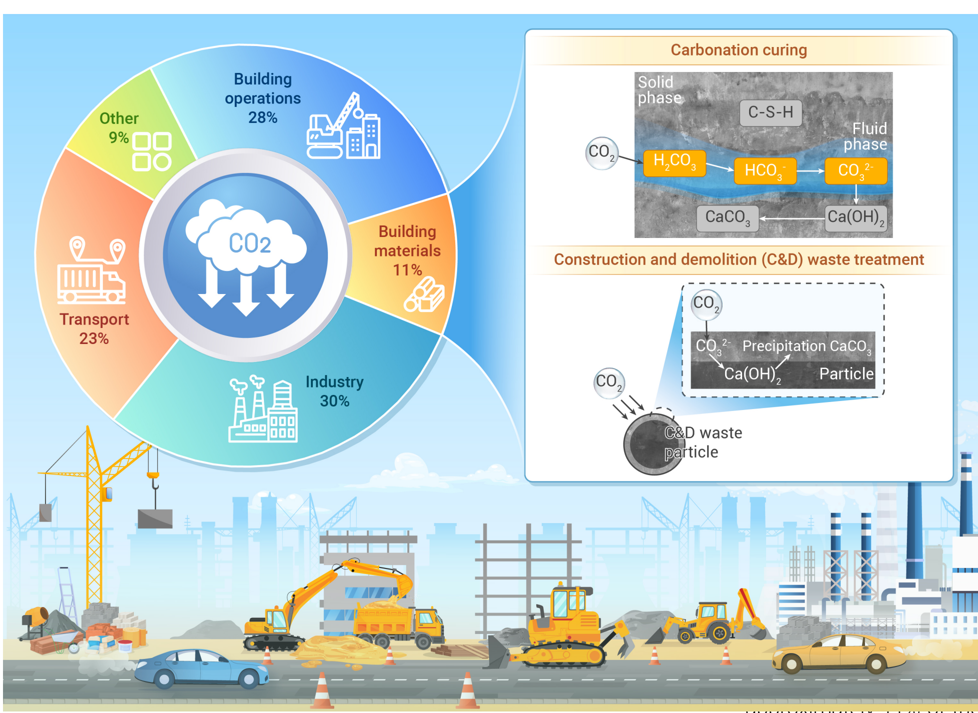

Figure 1. Global CO_2 emissions by sectors.

Carbonation curing involves exposing fresh cement or concrete mixtures to controlled CO_2 environments within a few hours after mixing. At this early stage, the mixture remains in a slurry state with an incompletely formed pore structure. This allows CO_2 to easily penetrate and react with exposed cement hydration products. Carbonation curing can also be applied to hardened cement paste, although in this case, the reaction occurs more slowly and is restricted to the surface due to reduced porosity. Due to these characteristics, carbonation curing is particularly suitable for thinner and more porous products, such as masonry units, paving stones, cement boards, fiberboards, and hollow masonry blocks.

... waste involves utilizing residual old cement paste ...tion and improve material properties. The primary ... in the carbonation reaction within C&D waste ...C_2S), $Ca(OH)_2$, and C-S-H. Research indicates that approximately 11% of the total calcium in waste cement can be carbonated, sequestering an estimated 0.27 tons of CO_2 per ton of waste cement.[3] Beyond emissions reduction, the carbonation of C&D waste improves the mechanical and durability properties of treated waste, making it a promising approach for sustainable construction practices.

MICP is an innovative biomineralization process that leverages microbial activity to produce $CaCO_3$.[4] This technology offers significant potential for carbon utilization and material enhancement in the construction industry. Annually, approximately 1.1 million tons of CO_2 are utilized in industrial processes, with 90% converted into chemicals such as urea and inorganic carbonates. Urea plays a critical role in MICP, serving as a key substrate for microbial metabolism. In this process, bacteria like Bacillus subtilis produce urease, catalyzing urea decomposition into ammonia (NH_3) and carbonic acid (H_2CO_3). The carbonic acid further decomposes into carbonate ions (CO_3^{2-}), which then combine with calcium ions (Ca^{2+}) to form $CaCO_3$. This precipitation process enhances the strength of cementitious materials by filling voids and refining microstructures. While MICP indirectly contributes to carbon utilization through the use of urea synthesized from industrial CO_2, recent advancements have explored the possibility of directly utilizing external CO_2 sources, such as atmospheric carbon dioxide or industrial emissions, as a carbon source in the precipitation process. In these systems, CO_2 is introduced into the microbial reaction environment, where it dissolves to form CO_3^{2-}. Microbial activity then induces the precipitation of $CaCO_3$, effectively sequestering CO_2 from external sources. These advancements open new pathways for MICP to function as a direct carbon utilization technology, further enhancing its environmental and sustainability benefits.

CHALLENGES FOR CARBON UTILIZATION IN CONSTRUCTION MATERIALS

CCUS technologies have emerged as critical solutions in the construction industry. Among these, the carbonation of construction materials demonstrates exceptional promise due to its simplicity, scalability, and efficient use of waste materials. Despite these advantages, several challenges must be addressed to fully realize the potential of carbon utilization in construction materials.

One significant challenge is the limited CO_2 penetration depth in concrete, especially in young or precast products. This limitation restricts the extent of carbonation and requires precise control of processing conditions, such as temperature, pressure, and moisture, to ensure consistent material properties. Another issue is the trade-off in mechanical properties. While moderate exposure to CO_2 can enhance compressive strength, prolonged exposure may have adverse effects, reducing the overall durability of the material. Furthermore, carbonation curing is mostly restricted to precast products due to the rapid hardening of the cementitious matrix. Expanding carbonation curing to other construction materials remains a challenge.

The variable composition of recycled concrete aggregates and waste cement is another obstacle. These variations affect the predictability of carbonation reactions, making it difficult to maintain consistent material quality. Developing standardized processes for handling and preprocessing recycled materials is essential to mitigate this issue. Additionally, the energy consumption and costs associated with carbonation processes may offset some of the carbon benefits, as processing and extended production times increase overall expenses. Lastly, challenges related to carbon accounting methods and the limitations of specific technologies must also be considered. Current carbon accounting standards often fail to capture the dynamic and long-term nature of carbon utilization, making it difficult to accurately quantify the carbon mitigation impacts of these technologies.

POTENTIAL FOR CARBON UTILIZATION IN CONSTRUCTION MATERIALS

Despite the challenges, mineral carbonation holds significant potential for commercial application in the construction industry. To achieve the 1.5°C global temperature control target, CO_2 emissions must be reduced by more than 80% by 2050, making CCUS technology critical for the construction sector.

Technological innovation plays a key role in overcoming existing barriers to the adoption of CCUS technologies. Continued advancements are expected to reduce costs and improve efficiency, making them more accessible and scalable. Research into advanced materials, such as nanomaterials and bio-based additives, offers further opportunities to enhance CO_2 uptake and improve the performance of carbonated materials. Policy support is another critical factor in driving the adoption of CCUS technologies. In China, the establishment of the "1+N" policy system for carbon peaking and neutrality has significantly bolstered CCUS-related initiatives.[5] Economic mechanisms, such as carbon pricing, are essential for creating a favorable environment for CCUS technology adoption in construction. Collaboration between academia, industry, and policymakers also plays a pivotal role in accelerating research, development, and commercialization efforts, ensuring that innovations are translated into practical implementation. Finally, standardization is a critical factor for the broader adoption of carbon utilization technologies. The development of standardized testing protocols and certification systems builds market confidence and promotes the wider adoption of carbon utilization technologies in construction applications.

CONCLUSION

Carbon utilization methods have demonstrated substantial potential to reduce emissions while enhancing construction material performance, with continuous advancements in research and innovation improving their feasibility, scalability, and cost-effectiveness. Furthermore, many countries and regions are also implementing supportive policies and regulations to promote CCUS adoption. Collaboration among academia, industry, and policymakers remains critical to accelerating the development of these technologies. By leveraging innovation and policy, the construction materials industry can play a pivotal role in achieving global carbon neutrality while advancing sustainable building practices.

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AUTHOR CONTRIBUTIONS

All authors contributed to the manuscript and approved the final version.

DECLARATION OF INTERESTS

The authors declare no competing interests.