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EDITORIAL: INSIGHTS ON THE POTENTIAL OF CARBON MINERALIZATION OF CONSTRUCTION MATERIALS

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Abstract — CO_2 emissions from the construction industry have long been a topic of global concern. While various efforts have been implemented and have shown promising outcomes, particularly the adoption of supplementary cementitious materials and the development of novel binders, these measures remain insufficient to meet the targeted net zero goals. Hence, new and advanced technologies are required to address the issue. Within the framework of carbon capture, utilization and storage (CCUS) technology, carbon mineralization of construction materials presents a viable approach to further drive the decarbonizing efforts of the construction industry. Carbon mineralization not only converts emitted CO_2 into stable carbonates for permanent storage within construction materials but can also improve the quality of the resulting materials and products, particularly those derived from waste, thereby supporting circular economy. Nevertheless, the widespread adoption of carbon mineralization technology in the construction industry remains limited. This is particularly due to challenges in translating the technology from laboratory and pilot studies to industrial-scale applications, where additional factors must be considered. Moreover, CO_2 sources are not always located close to carbon mineralization processes. Hence, addressing the associated challenges is crucial to enable the large-scale implementation of this technology for national benefits.

Keywords: Carbon mineralization, construction materials, embodied carbon emission, carbon capture and utilization, decarbonization

1.0 INTRODUCTION

The construction industry has long been associated with high CO_2 emissions. In 2022, the industry accounted for approximately 33% of global CO_2 emissions, representing a significant increase from the 20% recorded in 1995. This increase is mainly attributed to the input from construction materials, such as cement, bricks, metals, and glass. Notably, cement alone accounts for approximately 28% of the industry's total carbon footprint [1], or around 7-8% of total global emissions [2,3]. The high emissions are mainly due to the energy-intensive clinker manufacturing process, which involves fuel combustion and the calcination of limestone.

From the perspective of construction materials, various efforts have been undertaken to reduce the high CO_2 emissions associated with materials used in the industry. The most common approach that has been widely adopted globally is the incorporation of supplementary cementitious materials (SCMs) to reduce the clinker-to-cement ratio. Reduced clinker demand leads directly to lower CO_2 emissions. Fly ash and ground granulated blast furnace slag are among the most common SCMs that have been widely adopted. Other strategies, such as improving cement kiln operational efficiency and adopting lower carbon fuels, have also contributed to emission reduction [4,5,6].

Nevertheless, while these measures are effective, they remain insufficient to offset the large amount of CO_2 emitted and to achieve the targeted carbon reduction goals [7]. Additionally, the SCMs may face supply shortages in the near future due to the planned phase-out of coal power plants and the shift from blast furnaces to electric arc furnaces in steel production, which may further limit the potential for emission reduction.

It is, therefore, becoming an urgency to explore alternatives to maintain or enhance the decarbonization achievements attained so far. Strategies such as the exploration of alternative SCMs and the development of alternative binders [8,9,10,11], including alkali-activated materials or geopolymers, and limestone calcined clay cement (LC^3), have gained significant attention. In addition to the continual efforts in advancing binders, the carbon capture, utilization, and storage (CCUS) technology has also received great attention due to its potential to significantly reduce CO_2 emissions, where emitted CO_2 is captured and subsequently reused or stored, depending on the intended application and the amount available.

This editorial scope focuses specifically on carbon mineralization (also referred to as carbon utilization or carbon capture and utilization (CCU) under the broader umbrella of CCUS, which is an emerging technology that has drawn interest in the construction industry [12]. Carbon mineralization not only improves the resultant properties of construction materials and products but also offers a permanent CO_2 sequestration pathway while enabling waste valorization [13]. However, there is currently a mismatch in scales between CO_2 emissions and utilization, meaning CO_2 utilization cannot typically serve as a stand-alone solution [14]. Therefore, recognizing the impacts of carbon mineralization and addressing the challenges in scaling up technology are crucial to achieving targeted CO_2 reduction goals.

2.0 CARBON MINERALIZATION OF CONSTRUCTION MATERIALS

Carbon mineralization typically occurs by introducing captured CO_2 into materials, particularly those Ca- and Mg-bearing materials, where the CO_2 is subsequently converted into stable carbonate products [15], and the quality of the resulting materials is often improved. Lately, carbon mineralization has emerged as a promising decarbonization pathway for the construction industry. Carbon mineralization can happen at various stages within the product lifecycle, spanning from raw material preparation and treatment to manufacturing, curing, and even the treatment of industrial and construction-related wastes. This has enabled the potential involvement of CCU technology for a diverse range of construction products, including but not limited to cementitious binder, recycled concrete aggregate [16], block [17], and concrete slurry waste [18]. In addition, recent studies have shown increasing attention toward the carbon mineralization of MgO-rich feedstocks, attributed to their global availability and potential applications in construction materials [19,20]. Overall, carbon mineralization of construction materials is particularly attractive as it not only improves the material or the product properties but also has the potential to simultaneously address the challenges of waste valorization and carbon sequestration.

Carbon mineralization of construction materials is typically performed using direct carbonation techniques [21], where CO_2 is directly introduced into the materials or products at the designated stages. For instance, zero-cement blocks made using low-hydraulic slags were manufactured and cured using CO_2 [17]. Additionally, coal fly ash was treated with direct carbonation to enhance its properties [21]. In contrast, while indirect carbonation [22] can also be adopted in the industry, they are more commonly adopted for resource recovery purposes. For indirect carbonation, the reactive components are first extracted before undergoing carbonation reactions. Pure calcium carbonate was successfully produced by precipitating the recovered calcium from 1-year-old waste hydrated cement paste [23].

3.0 BENEFITS AND LIMITATIONS OF CARBON MINERALIZATION OF CONSTRUCTION MATERIALS

Carbon mineralization of construction materials presents significant opportunities for the construction industry to contribute to global decarbonization efforts. One of its key benefits is its ability to convert CO_2 into stable mineral forms, with calcium carbonate being one of the most common carbonates formed during carbon mineralization in construction materials [24]. Additionally, as the formation of carbonate mineral is thermodynamically favorable [25], long-term stability and permanent CO_2 sequestration can be achieved. It has also been reported that substituting 10% of construction materials with CO_2-mineralized products can reduce CO_2 emissions by 1.6 billion tonnes per year [26].

While carbon mineralization demonstrates promising CO_2 sequestration potential, it also shows promise in enhancing the performance of construction materials. A zero-cement block produced with low-hydraulic slag exhibited significant strength improvement when subjected to CO_2 curing, increasing from around 5 MPa to 25-37 MPa [17]. Moreover, this enhancement is not only observed in virgin raw materials or cast products but also in waste materials. For instance, the quality of recycled concrete aggregate derived from concrete and demolition waste can be improved due to densification of its microstructure after carbonation. This addresses the inherently inferior performance of non-carbonated recycled concrete aggregate, which is attributed to the adhered mortar on the surface and the existence of micro-crack damage [27,28]. With this improvement, the utilization rate of recycled materials can be increased. In addition, carbon mineralization facilitates a more uniform in situ dispersion of $CaCO_3$ throughout the material, whereas externally added $CaCO_3$ typically requires specialized dispersion techniques [29].

On the other hand, indirect carbon mineralization can facilitate the recovery of valuable materials, such as rare earth elements and metal elements, during the pH-swing process. The resulting carbonates are typically of high purity, and any excess can be stored underground [23]. Hence, through thoughtful and systematic planning and design, the potential of carbon mineralization extends beyond emissions reduction. It can also enhance the performance of the resulting products while enabling the recovery of valuable materials. Overall, carbon mineralization represents a sustainable and multifaceted solution, addressing global emissions challenges while promoting sustainability and the circular economy.

However, while carbon mineralization offers attractive benefits to the construction industry, several challenges remain and need to be addressed to enable its broader implementation. One major challenge is the availability and transportation of captured CO_2. Unlike the cement manufacturing industry, which can directly utilize its flue gas for carbon mineralization, in many cases, the sources of CO_2 emissions and the production facilities are separated. This results in additional costs and complexity due to the logistics and infrastructure required for CO_2 capture, purification, and transport.

Another critical challenge relates to the scalability of carbon mineralization processes. Most investigations conducted so far, although demonstrating promising outcomes, are limited to laboratory and pilot-scale studies. In addition, the variability of materials, particularly those waste materials, may become another barrier. Variations in their chemical composition, particle size distribution, and reactivity can affect carbonation efficiency and the resulting carbonate phases. This has made translating the technology into industrial-scale applications require further optimization, considering process efficiency and economic feasibility, etc. Furthermore, the CO_2 curing process typically requires an enclosed chamber, making it unsuitable for large-scale on-site construction projects [30].

4.0 CONCLUSIONS AND FUTURE RECOMMENDATIONS

Various measures have been adopted to address the high CO_2 emission problem of the construction industry for decades. However, to achieve the net-zero emission goals by 2050, the current decarbonizing strategies may not be sufficient. Moreover, a minimum of 9 billion tonnes (10 billion tons) of CO_2 shall be removed annually to avoid catastrophic global warming by 2050 [26]. This has prompted the construction industry to explore new and more advanced approaches to further enhance the decarbonization efforts, especially in reducing embodied CO_2 that is relatively hard to abate. Carbon mineralization of construction materials provides a promising pathway to enhance the decarbonization roadmap. In addition to complementing existing efforts, carbon mineralization can enhance the performance of construction materials and products. It also supports the circular economy, as the quality of recycled materials derived from industrial and construction-related waste can be enhanced after adopting the carbon mineralization approach. Nonetheless, several challenges remain that must be addressed to enable the widespread adoption of this technology, particularly in accelerating the translation of the technology to industrial-scale applications. To support the drive, subsidies and funding, along with stronger collaboration between government and industry, could act as key accelerators. Additionally, the development of standards and guidelines is essential to facilitate market acceptance, as adoption of this technology may alter the properties of materials and products. Moreover, changes to the current operation practices, including quality control processes [14], are expected.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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