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Innovative strategies for carbon dioxide retention in the curing process of precast plain mass concrete elements

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Abstract. Research on carbon dioxide capture and storage technologies through accelerated carbonation of cement-based materials, is gaining increasing interest in the construction sector. This study aims to present the capacity of carbon dioxide (CO_2) capture and storage, as well as the effects of the carbonation on the physical and mechanical behaviour of precast vibrated plain mass concrete elements. The analysis includes various methods to enhance the efficiency of the carbonation process and accelerate it, emphasizing the importance of optimizing reaction conditions. The research findings suggest that the carbonation process can significantly improve the mechanical performance of these precast elements, making them more durable and efficient. Critical parameters, such as water content, sample size, environmental pressure, and temperature, considerably influence the efficiency of carbon dioxide capture. Furthermore, the study proposes directions for implementing rapid CO2 sequestration technologies, highlighting their potential to contribute to decarbonization. The research aims to open new perspectives for the use of plain mass concrete precast elements while facilitating the exploration of innovative solutions in the context of sustainable development. In conclusion, the carbonation of precast concrete elements proves to be a promising approach in the fight against climate change, with direct applications in the construction industry and beyond.

1 Introduction

The construction industry is one of the largest contributors to global carbon dioxide (CO_2) emissions, accounting for around 8% of total global emissions [1]. The production of cement, an essential material for concrete, generates significant amounts of CO_2 both through the chemical process of limestone calcination and through high energy consumption. According to recent estimates, between 0.6 and 0.9 tons of CO_2 are released into the atmosphere for every ton of cement produced [2]. Given the increasing demand for sustainable building materials, the adoption of carbon footprint reduction technologies is becoming a global necessity.

One of the emerging solutions is accelerated carbonation, a process by which CO_2 reacts with alkaline compounds in cement, in particular calcium hydroxide ($Ca(OH)_2$), to form calcium carbonate ($CaCO_3$). This chemical reaction is well known in the natural environment, where concrete undergoes a slow carbonation process during its lifetime. However, accelerated carbonation technology allows this process to be intensified by capturing carbon dioxide in a controlled and permanent way [3].

In addition to reducing CO_2 emissions, this process also improves the mechanical properties of concrete, helping to increase compressive strength, reduce permeability and improve the durability of the material against aggressive agents. Studies show that concrete treated by accelerated carbonation can have 15-30% higher mechanical strength compared to traditional concrete, due to the formation of a more compact calcium carbonate matrix [4].

Another important advantage of this technology is its applicability in the production of precast elements, where process parameters can be optimized to maximize CO_2 absorption. Precast concrete precast elements, such as masonry blocks, pavers and precast panels, are ideal for this type of treatment as they can be exposed in controlled environments, accelerating the chemical reaction and ensuring efficient CO_2 fixation [5].

In addition, accelerated carbonation can play an important role in the circular economy by enabling the use of industrial wastes as feedstocks for carbon capture. For example, recycled concrete residues, metallurgical slag and fly ash can be used as calcium sources for the carbonation reaction, thus reducing the need for extraction of natural raw materials [3]. This sustainable approach not only helps to manage waste, but also to produce more environmentally friendly and efficient building materials.

As international regulations are becoming increasingly stringent on low-carbon emissions, governments and companies are investing in carbon capture, utilization and storage (CCUS) solutions to transition to low-emission buildings. For example, the European Green Deal calls for a 55% reduction in net greenhouse gas emissions by 2030, and carbon-based technologies could make a significant contribution to

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achieving this target. At the same time, international standards for sustainable construction, such as LEED (Leadership in Energy and Environmental Design) and BREEAM (Building Research Establishment Environmental Assessment Method), encourage the use of building materials with low environmental impact [4].

Although accelerated carbonation has multiple advantages, implementation at industrial scale is still limited by high upfront costs, the need to adapt technical standards and the lack of infrastructure needed to capture CO_2 at source. However, recent research is exploring methods to optimize the process, including adjusting CO_2 pressure, humidity and temperature in the treatment chambers to maximize reaction efficiency [5].

Thus, accelerated carbonation has the potential to transform the construction industry into a more sustainable sector, contributing to the reduction of greenhouse gas emissions, the improvement of concrete properties and the integration of circular economy principles. This paper reviews the literature on accelerated carbonation of precast elements, highlighting reaction mechanisms, technological benefits and industrial implementation challenges. Future research directions and process optimization strategies are also discussed, considering both the environmental efficiency and economic feasibility of this innovative technology.

2 Materials and methods

This section is based on a detailed review of the literature on mass concrete carbonation, exploring recent research on the mechanisms of the chemical reaction, the factors influencing the process and its impact on concrete properties. Accelerated carbonation is a process in which CO_2 reacts with calcium hydroxide ($Ca(OH)_2$) in cement, generating calcium carbonate ($CaCO_3$) and water, which results in a reduction in concrete porosity and an increase in compressive strength [6].

The efficiency of this process is influenced by several factors, including the concentration of CO_2, initial concrete moisture, temperature and exposure time. Studies show that a CO_2 concentration between 15-30% in a controlled environment leads to an acceleration of the reaction, while optimal moisture levels between 50-70% favour the reactivity of concrete to carbonation [7]. Also, temperatures between 20-60°C significantly accelerate the process and a higher initial porosity may facilitate carbon dioxide penetration, although this may have a negative effect on the final mechanical strength [5].

In the context of industrial applications, the technology of manufacturing precast elements from vibro-prestressed mass concrete plays an essential role in optimizing the durability and mechanical performance of these products. Vibro-pressing combines the processes of simultaneous vibration and pressing, resulting in concrete with high density and low porosity, which are essential characteristics for improving compressive strength and freeze-thaw behaviour [8]. This technology is commonly used to manufacture products such as pavers, masonry blocks and kerbs, and its automated process allows optimizing material consumption and reducing manufacturing time.

The manufacture of vibro-prestressed mass concrete elements involves several successive stages, each with a significant impact on the quality of the final product. The first stage involves the selection and proportioning of raw materials - cement, aggregates, and water - according to established recipes. Subsequently, the materials are mixed in an industrial mixer, resulting in a homogeneous mass concrete that is poured into special moulds and placed on the platform of a vibro-pressing machine [9].

During vibro-pressing, the concrete is subjected to high-frequency vibration and high mechanical pressure, which results in optimal compaction of the material and the removal of air from the mixture. This process produces products with high density and improved strength.

The technological flow for the realization of vibropressed elements is schematically shown in Fig. 1.

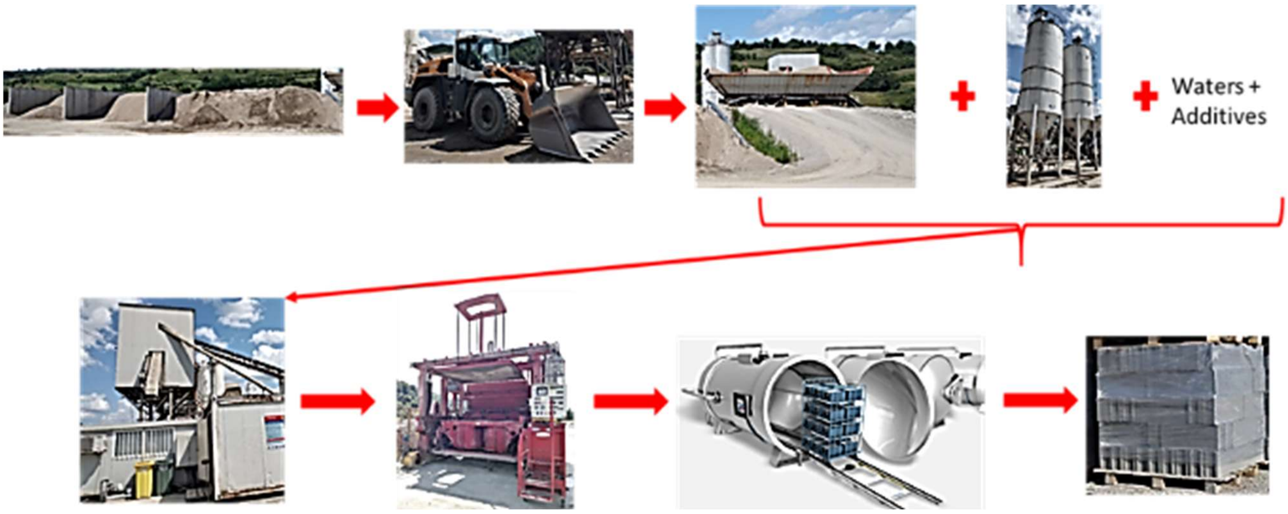

Fig. 1. Schematic presentation of the process of making prefabricated mass concrete elements by conditioning them with CO_2

After vibro-pressing, the elements are extracted using specialized devices to prevent damage to the edges and are transferred onto pallets or conveyor belts to be moved to the curing area. The hardening of concrete can take place naturally or can be accelerated by the application of steam or heat, depending on the technical requirements of the product. In this context, the use of controlled curing chambers allows humidity and temperature to be regulated, thus optimizing the curing process of precast elements.

The production of vibro-prestressed precast mass concrete elements requires specialized equipment such as industrial mixers for homogenizing the mixture, vibro-pressing machines that simultaneously apply vibration and pressure, reusable metal or plastic moulds, transport and handling systems, and curing chambers to accelerate the curing process. This equipment ensures efficient and sustainable production, reducing material waste and energy consumption.

The integration of the vibro-pressing process with accelerated carbonation technology offers a high potential for improving the performance of precast elements, enabling both CO_2 capture and storage and extended product durability. As international standards promote solutions to reduce the carbon footprint of building materials, this technology combination can become a key strategy in the transition towards a more sustainable construction industry.

3 Results and discussions

The literature review, summarized by the analysis of publications in WOS indexed journals, indicated an accelerated upward trend of interest in both the technology of making precast mass concrete elements and the accelerated concrete carbonation process. As shown in Fig. 2, using the keyword "precast concrete", it can be observed the strong growth of research interest and the maintenance of the upward trend, starting after 2010, with the mention that the information for 2025 is being completed. Similarly, using the keyword "accelerated carbonation of concrete", 2105 publication items were found, accumulating more than 70000 citations in almost 30000 specialized papers, Fig. 3. Even this less in-depth analysis indicates a strong research interest, on the one hand, in the use of technologies for the realization and installation of precast mass concrete elements, and on the other hand in an innovative way of curing mass concrete, while reducing the related technological times through controlled exposure to CO_2.

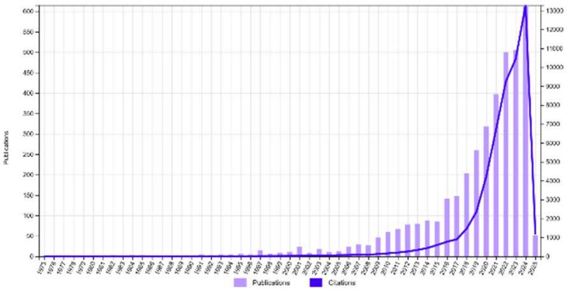

Fig. 2. Evolution of WOS publications and related citations using the keyword "precast concrete"

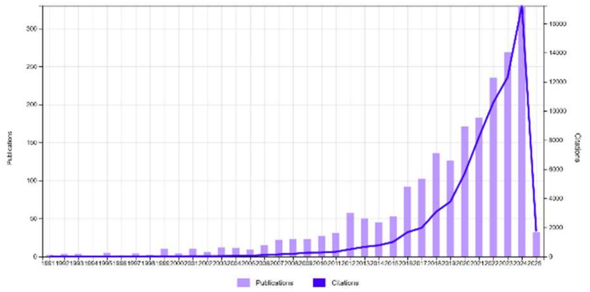

Fig. 3. Evolution of WOS publications and related citations using the keyword "accelerated carbonation of concrete"

The manufacture of precast vibroprestressed mass concrete precast elements is an industrially optimized process, influenced by the technological parameters and the composition of the material used. The performance of these elements is directly dependent on the type of cement, the nature and granularity of the aggregates, the proportions of water and additives, as well as the vibro-pressing process and the curing method applied. The literature emphasizes that the use of recycled industrial wastes, such as granulated blast furnace slag (GGBS), fly ash and limestone dust, is a sustainable strategy that contributes to reducing the environmental impact without compromising the mechanical properties of concrete [1].

One of the most important parameters in the manufacture of vibropressed mass concrete is the water/cement ratio (w/c), which influences concrete workability, compactability and ultimate strength. Studies indicate that an optimum ratio between 0.36 and 0.43 allows to obtain a dense structure and to reduce shrinkage during curing [3]. Mechanical compaction by vibro-pressing plays an essential role in obtaining low porosity products, influencing their compressive strength and durability. The process involves the simultaneous application of high pressure and high-frequency vibration, which contributes to the removal of air from the mixture and the uniform distribution of cement and aggregate particles in the mould [10]. The use of a vibration frequency between 50 and 100 Hz has been shown to improve concrete compaction without affecting the internal structure of concrete [4].

The method of curing mass concrete has a major impact on its mechanical properties and long-term behaviour. Natural hardening is the simplest method, taking place at ambient temperatures, but it requires a long time (7-28 days) to reach optimum strength. Steam hardening is commonly used in industrial production, accelerating the curing of mass concrete to temperatures of 50-80°C, which allows high initial strength to be achieved within the first 12 hours. However, this method can cause rapid shrinkage and cracking of concrete if the process is not properly controlled [5].

A sustainable alternative to conventional curing methods is accelerated carbonation, a technology that utilizes carbon dioxide (CO_2) to improve the density and mechanical strength of concrete. The chemical reaction between CO_2 and calcium hydroxide ($Ca(OH)_2$) in cement leads to the formation of calcium carbonate ($CaCO_3$), which contributes to the hardening of concrete and reduces its porosity [6]. Studies show that exposing vibroprestressed mass concrete to a CO_2-rich atmosphere for 12-24 hours can increase compressive strength by 15-30% and reduce water permeability, which improves the durability of the final product [7].

Comparison of curing methods shows that each technology has advantages and limitations. Natural curing is economical and requires no special equipment, but it is slow and can lead to variations in product quality. Steam curing is efficient in mass production, providing rapid ripening, but consumes significant energy. In contrast, accelerated carbonation curing reduces the carbon footprint of concrete, improves product durability, and contributes to the permanent sequestration of CO_2 in the concrete structure, making this method a viable option for the construction industry [11,12].

The use of eco-sustainable composite materials in construction has been intensively studied in recent years, and recent research shows that their integration in the production of precast elements can significantly contribute to reducing the carbon footprint and improving mechanical performance [13,14]. Also, comparisons between self-compacting concrete and vibrated mass concrete, carried out in various experimental studies, have revealed important differences in mechanical behaviour and curing efficiency by different methods. Studies have shown that self-compacting concrete, due to its high fluidity, can facilitate a more uniform distribution of carbonatization, thus increasing the degree of CO_2 reaction and improving the long-term performance of the material.

The application of accelerated carbonation on an industrial scale brings multiple benefits in terms of both sustainability and mechanical performance. By integrating this method into the production process, higher strength prefabricated elements can be obtained, better able to withstand aggressive factors such as freeze-thaw cycles and chemical attack. The use of this method can also reduce operational costs by eliminating the need for high temperatures for rapid curing of concrete [15].

4 Conclusions

The literature study confirms that the accelerated carbonation process applied to vibro-pressed mass concrete precast elements brings significant benefits in terms of both mechanical properties and sustainability of the building materials. Through the chemical reaction between CO_2 and cement compounds, the porosity of the mass concrete is reduced and the compressive strength is improved. This process allows carbon dioxide to be captured and stored, thus helping to reduce industrial emissions and promote environmentally friendly construction practices.

Compared to traditional curing methods, accelerated carbonation offers an efficient alternative, eliminating the need for the high energy consumption used in steam curing. In addition, the results of experimental studies show that mass concrete elements treated by this process exhibit higher density and reduced permeability, making them more durable and resistant to degradation factors such as freeze-thaw cycles and chemical attack.

In terms of manufacturing technology, vibro-pressing combined with accelerated carbonation optimizes the compaction of the material, leading to higher quality products. The use of composites and industrial waste in concrete mixes is also a viable solution to reduce the consumption of natural raw materials, facilitating the transition to a circular economy [16-18].

The integration of this technology in the industrial production of precast concrete can have a positive impact on the efficiency of manufacturing processes, reducing curing time and associated costs. In the long term, the widespread adoption of accelerated carbonation could significantly contribute to reducing the carbon footprint of the construction industry and achieving sustainable development goals.

However, large-scale implementation requires technological adaptations, investment in specialized equipment and the establishment of clear regulations for the use of this method in concrete production. Future research should focus on optimizing the reaction parameters, analyzing the effects of long-term carbonation on the mechanical behaviour and durability of structures made of carbonated mass concrete.

Thus, accelerated carbonation of precast vibroprestressed concrete elements is emerging as a promising solution in the transition towards more durable, efficient and environmentally friendly construction materials.

In addition, the use of this technology could be extended to other types of precast mass concrete, including complex structural elements used in infrastructure and residential buildings. Another important advantage of accelerated carbonation is its ability to improve the aesthetic properties of mass concrete, due to reduced efflorescence and a more uniform surface appearance. Recent research also shows that the carbonation process can influence the microstructure of the cementitious matrix, which could lead to better compatibility with other materials used in construction, such as fibers or composites.

In the future, the development of advanced methods to monitor the carbonation process could contribute to increased industrial efficiency and the implementation of clear standards to produce low carbon footprint concrete. Collaboration between research institutes, the cement industry and the construction sector will also play a key role in accelerating the transition to more sustainable technologies. In conclusion, accelerated carbonation is not only an innovative method for hardening concrete, but also an essential strategy for reducing environmental impact and developing the buildings of the future.

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