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Review

Evaluating the Impact of CO_2 on Calcium SulphoAluminate (CSA) Concrete

Daniel D. Akerele * and Federico Aguayo

Department of Construction Management, University of Washington, Seattle, WA 98195, USA; aguayo12@uw.edu
* Correspondence: dannie70@uw.edu

Abstract: The construction industry is a significant contributor to global CO_2 emissions, primarily due to the extensive use of ordinary portland cement (OPC). In response to the urgent need for sustainable construction materials, calcium sulphoaluminate (CSA) cement has emerged as a promising alternative. CSA cement is renowned for its low carbon footprint, high early-age strength, and superior durability, making it an attractive option for reducing the environmental impact of construction activities. While CSA cement offers benefits in carbon emissions reduction, its susceptibility to carbonation presents challenges. Although the body of literature on CSA cement is rapidly expanding, its adoption rate remains low. This disparity may be attributed to several factors including the level of scientific contribution in terms of research focus and lack of comprehensive standards for various applications. As a result, the present study sets out to track the research trajectory within the CSA cement research landscape through a systematic literature review. The study employed the Prefer Reporting Item for Systematic Review and Meta-Analysis (PRISMA) framework to conduct a literature search on three prominent databases, and a thematic analysis was conducted to identify the knowledge gap for future exploration. The study revealed that while CSA concrete demonstrates superior early-age strength and environmental resistance, its susceptibility to carbonation can compromise structural integrity over time. Key mitigation strategies identified include the incorporation of supplementary cementitious materials (SCMs), use of corrosion inhibitors, and optimization of mix designs. The review also highlights the global distribution of research, with notable contributions from the USA, China, and Europe, emphasizing the collaborative effort in advancing CSA concrete technology. The findings are crucial for enhancing sustainability and durability in the construction sector and advancing CSA binders as a sustainable alternative to traditional cement.

Keywords: concrete; calcium sulphoaluminate cement (CSA); mechanical properties; carbonation (CO_2); durability; sustainability

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1. Introduction

The global push for net zero carbon emissions necessitates combined efforts from all sectors. Nañagas et al. (2022) [1] describe CO_2 as a dangerous gas to both humans and the environment. Carbon footprint is one of the most discussed topics in recent times due to climate change challenges such as flooding, heat waves, extreme weather, extinction, and even death [2,3]. Carbon emissions, including all greenhouse gases (GHGs), are major contributors to climate change. Among the sectors contributing to GHG emissions, the construction industry ranks second, accounting for over 40% of global emissions from buildings alone [4].

Concrete production, particularly cement production, is a significant contributor to these emissions. Cement production accounts for over 8% of global CO_2 emissions [5]. For instance, one ton of cement typically produces about 0.8 to 0.9 tons of CO_2 emissions, accounting for approximately 8% of the world's anthropogenic CO_2 emissions [4]. Understanding these emissions and developing strategies to reduce the carbon footprint from concrete production is crucial for contributing to global efforts to mitigate climate change.

Recent studies regarding life cycle assessment of buildings have in fact attributed up to 90% of embodied carbon emission to the A1–A3 (raw material extraction, transportation, and on-site construction) stages of whole building lifecycle assessment in extreme cases, about 25% in conventional buildings, and up to 50% in advanced construction [6]. Understanding and managing these stages are essential for sustainable construction practices.

Concrete is the most widely used building material globally, and its production thus significantly contributes to GHG emissions. The primary source of these emissions is the manufacturing of cement, a key component of concrete [7]. According to Shen et al. (2014) [8], cement production ranks second in global CO_2 emissions, with portland cement production accounting for about 80% of CO_2 emissions in concrete. The CO_2 emissions from portland cement result from the calcination of limestone ($CaCO_3$) and the combustion of fossil fuels, including the energy required in cement production plants. To produce portland cement clinker, limestone is heated with a source of silica in a kiln at temperatures over 1350 °C, making both the process and its byproducts harmful to the environment [9].

Advances in construction have sought means to address this issue, aligning with sustainability development goals by drastically reducing carbon emissions especially at the production point [10]. One approach is to provide alternative binders that produce less carbon than conventional portland cement [11]. Alternative cement materials, such as calcium sulphoaluminate cement (CSA) and other supplementary cementitious materials (such as fly ash, metakaolin, and silica fume), have been proven to produce less carbon [12]. Studies reveal that they reduce carbon emissions at the production point by about 50% compared to portland cement [13–15].

However, one of the challenges with these alternative cement materials is their susceptibility to concrete carbonation compared to portland cement [16]. Although they generally show higher early-age strength and superior properties compared to portland cement [17], carbonation poses significant threats especially to reinforced concrete over its lifespan, including accelerating corrosion of reinforcing rebar [18]. Assessing the impact of carbonation on alternative cement materials like CSA helps better understand the concrete produced with these materials and tackle the problems faced with carbonation. Studies such as those of Guo et al. (2014) [16,17] have highlighted that alternative cement materials like CSA are more prone to carbonation than portland cement, despite their higher early-age strength and superior properties. Additionally, carbonation reactions can pose significant threats to reinforced concrete over its lifespan, including accelerating the corrosion of reinforcing rebar [19]. Korec et al. (2024) [20] conducted an interesting study on predicting carbonation-induced corrosion in concrete with rebars, which included modelling framework for predicting carbonation and understanding the behavior of carbonated concrete; this gives an interesting insight into understanding the behavior of reinforced CSA concrete. Regrettably, the impact of CO_2 on CSA is still not fully understood. These limitations in the existing body of literature serve as a point of departure for the current study. Accordingly, this review sets out to investigate the impact of carbonation on CSA cement through a systematic literature review.

The findings of this study will be valuable to the construction industry and may influence how buildings and transportation infrastructure, including precast structures using CSA concrete, are designed and constructed in the future to provide mitigation against the downside effect of CSA concrete carbonation. Additionally, this study could also inform policy decisions and regulations regarding the use of alternative cement materials, including calcium sulphoaluminate cement, as a means to decarbonize the construction industry. The review could also contribute to the development of new technologies and methods for mitigating the impact of CO_2 on concrete structures, thereby advancing the field of sustainable construction.

2. Systematic Literature Methodology

The current study employed the Prefer Reporting Item for Systematic Review and Meta-Analysis (PRISMA) framework to trace the research output on calcium sulphoaluminate (CSA) cement in cement production domains within a period of about eleven years. Specifically, the study aims to focus on the impact of CO_2 on CSA concrete and exclude articles that delve into discussions of other CSA concepts such as the barriers, applications and adoption as these aspects have been addressed by various authors. As a result, this review followed specific criteria for selecting articles. At first, preference was given to peer-reviewed articles available in open-access databases to enhance the study's replicability and transparency. This approach ensured that other researchers could access and verify the findings, thereby contributing to the overall robustness of the investigation [21].

Additionally, the articles included span from 2012 to the first quarter of 2024. This timeframe was intentionally selected to cover the critical early stages of calcium sulphoaluminate cement development. Furthermore, only manuscripts written in English were chosen to ensure broader accessibility, recognizing English as a widely accepted global language [22]. More importantly, it was a requirement that the words 'CO_2 OR Carbonation', 'Calcium SulphoAluminate', or 'CSA' and 'cement', must be present in the title, abstract, or keyword of the article. However, this condition might exclude some relevant articles. Nevertheless, it ensured that only those related to calcium sulphoaluminate cement were selected, thereby eliminating redundant manuscripts from the selection process.

The literature search was performed across multiple reputable databases, including Google Scholar, Scopus, and Web of Science, covering peer-reviewed journals, conference proceedings, and technical reports. These databases were selected because of their reputation for publishing peer-reviewed materials and the availability of robust studies in the subject area. Additionally, consulting three databases allows for validation and cross-verification, diverse perspectives, and diverse methodologies, and ensures comprehensive data collection. The search terms included "CO_2 impact on CSA concrete", "carbonation of calcium sulphoAluminate cement", "alternative cement materials", and "sustainable construction materials". The search was conducted based on the following criteria: relevance to research questions; focus on CSA cement and its interaction with CO_2; studies published with the selected temporal period; and availability of detailed experimental methodologies and findings.

The data extraction process involved identifying materials used, experimental methods, key findings, novelty of the research, research gaps, and recommendation for future directions. This information was evaluated and synthesized to identify common themes, trends, and literature gaps using a thematic approach [23]. The methodological approach also considered the reliability and validity of the reviewed studies, assessing their study designs, sample sizes, and experimental conditions.

3. Results and Discussion

3.1. Results

The stringent selection criteria of the study led to the identification of 1265 articles. In total, 500 articles were identified from Google Scholar while 375 and 390 articles were identified from Web of Science (WoS) and Scopus, respectively. Figure 1 provides the flowchart illustrating the steps for the article selection and the details of the materials used for qualitative and quantitative synthesis.

Figure 2 illustrates the number of publications per year related to the impact of CO_2 on calcium sulphoaluminate (CSA) concrete from 2012 to the second quarter of 2024. The data indicate fluctuations in research interest over this period, reflecting various factors influencing the research community.

The analysis of the population trend indicates that in the early years (i.e., 2012–2015) there is a moderate number of publications. This period likely represents the early exploration phase of research into CSA cement and its carbonation properties. The initial years show a modest number of publications, indicating the early stages of research into CSA cement. During this period, researchers were primarily focused on understanding the fundamental properties and potential benefits of CSA cement. For instance, studies like those by Mechling et al. (2014) [24] highlighted the basic behaviors of sulphoaluminate cements under various environmental conditions, setting the stage for subsequent research by demonstrating the potential of CSA cement under different environmental conditions However, there is a noticeable increase in the number of publications in the mid period (between 2016 and 2020). This period marks a significant growth phase where CSA cement's potential benefits in reducing CO_2 emissions and enhancing sustainability were increasingly recognized. During this time, studies explored various aspects of CSA, including the chemical interactions between CO_2 and CSA cement, mechanical properties, and durability under different environmental conditions (e.g., [25–27]). In the most recent years (2021–2024), heightened interest and possibly increased funding and policy support for sustainable construction materials were observed. This period coincides with global initiatives to reduce carbon footprints in the construction industry. For example, the work by Ansari et al. (2022) [28] proposed novel approaches to improving the carbonation resistance of CSA cement, showcasing innovative solutions to existing concerns. Sharma et al. (2023) [29] also emphasized the microstructural characteristics and CO_2 uptake of CSA cement, further driving interest in this field.

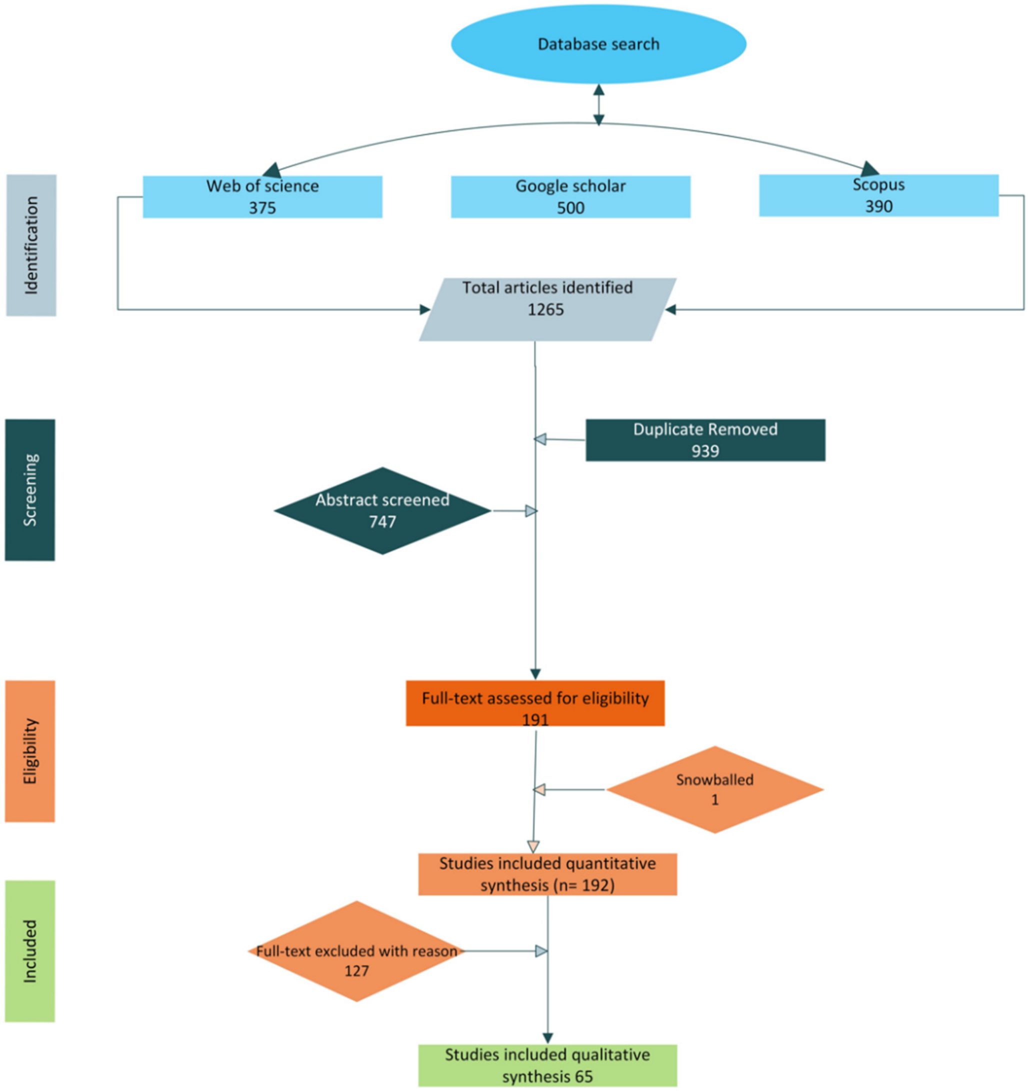


Figure 1. Articles selection process.

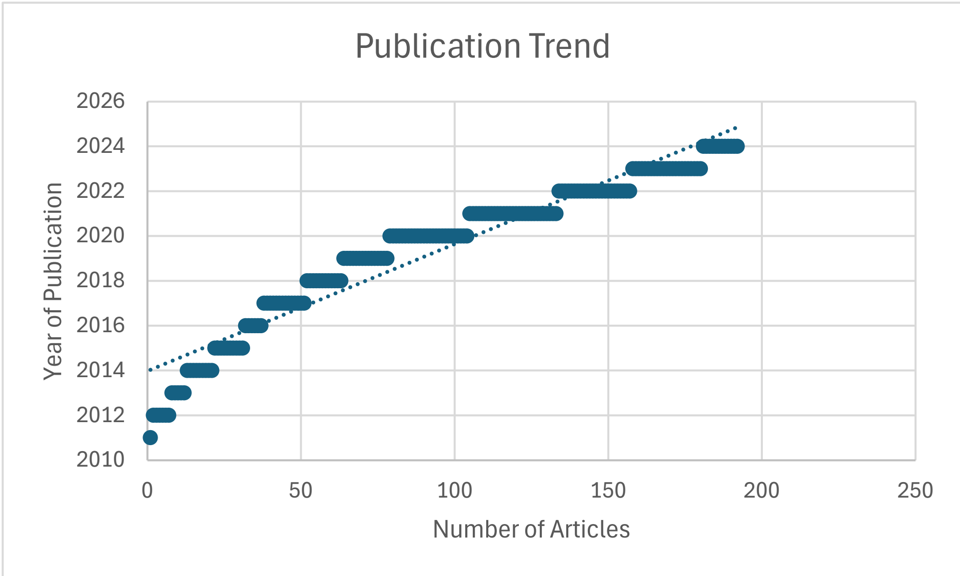


Figure 2. Publication trend.

Figure 3 provides a breakdown of the journal sources for the articles included in the quantitative synthesis. The chart illustrates the top 10 journal sources by the number of publications. The breakdown of journal sources indicates that research on the impact of CO_2 on CSA concrete is published across a variety of journals, with a concentration in a few leading ones. Most of the publications are concentrated in journals such as Construction and Building Materials, Cement & Concrete Composites, and Cement and Concrete Research, accounting for 35% of the total articles selected for eligibility. These journals are highly regarded in the field of construction materials and concrete research, indicating that studies on CSA cement and CO_2 impact are recognized and valued within these specialized publications [30].

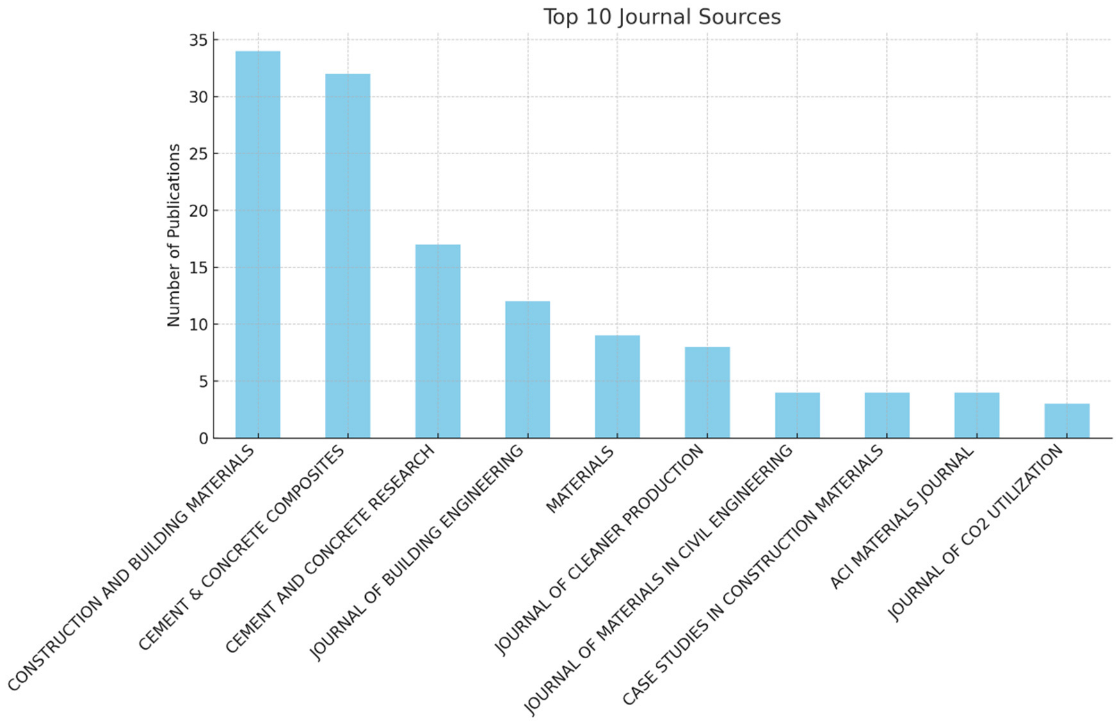


Figure 3. Publication outlet.

The wide range of journals, from Journal of Building Engineering to Journal of Cleaner Production, reflects the interdisciplinary nature of this research area. High-impact journals like Cement and Concrete Composites and Construction and Building Materials lead in publishing major findings, while specialized journals such as Coatings, Sustainability, and Journal of CO_2 utilization provide platforms for focused and interdisciplinary studies. This balanced dissemination ensures comprehensive coverage of both fundamental and applied aspects of CSA cement research, promoting its development as a sustainable construction material.

Figure 4 is used to present a breakdown of journal sources by country. Understanding country distribution of research studies on CSA and its carbonation properties would help in understanding the regions that are contributing the most on the subject, providing an overview of global interests and engagement in this field. Such analysis can help to identify nations with advanced research facilities and significant investment in construction materials. It is also useful to visualize global trends in CSA cement research, such as which countries are championing new methods and technologies. This will also inform researchers and professionals about current state and emerging areas of interest.

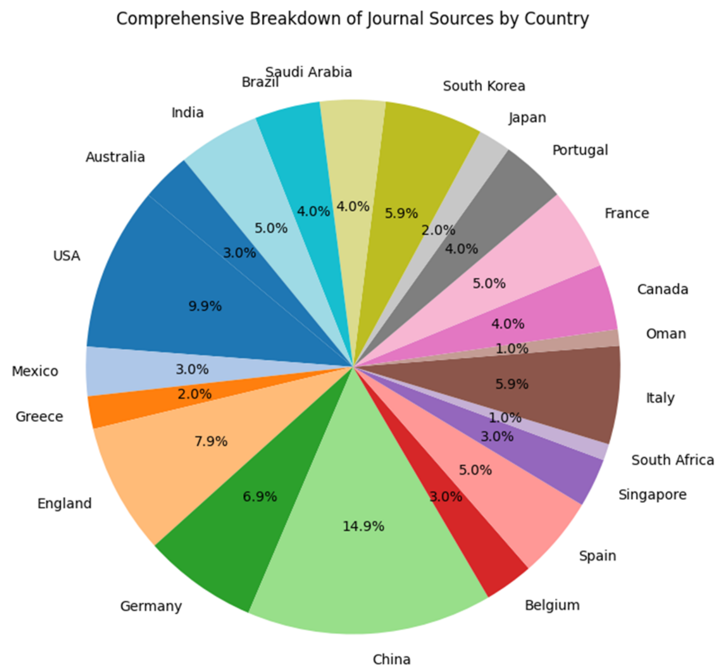


Figure 4. Countries of publications.

Furthermore, policymakers and stakeholders can use the country distribution data to make informed decisions regarding allocation of resources and funding, and to strategically come up with initiatives for sustainable construction. Finally, these data can also inform research collaborations, motivate researchers, and foster technology transfer across industries.

3.2. Discussion

Bibliometric Analysis

Advanced studies have focused on optimizing CSA cement formulations, assessing long-term performance, and scaling up applications for broader industry use. The trend in publications aligns with this study's objectives, which aim to systematically review and synthesize existing research on the impact of CO_2 on CSA concrete. The growing body of literature provides a robust foundation for analyzing trends, identifying gaps, and proposing future research directions. Several key studies highlight the relevance of the observed trend; for example, Bertola et al. (2019) [31] investigated the carbonation resistance of CSA cement and its implications for durability and environmental impact.

Similarly, Monkman (2018) [32] explored the chemical mechanisms of CO_2 interaction with CSA cement, providing insights into optimizing its formulation for enhanced performance, and Vaishnav Kumar Shenbagam et al. (2024) [33] conducted a comprehensive review of sustainable cement materials, emphasizing the importance of CSA cement in reducing the carbon footprint of the construction industry. These studies underscore the importance of understanding the impact of CO_2 on CSA cement and support the increasing research interest reflected in the publication trends.

The top five countries in terms of publications include the USA, China, England, Germany, and Italy, respectively. This reflects the significant contributions from these countries in construction materials and CSA cement research. The research on CSA cement is fairly distributed globally, with contributions from countries across different continents including North America, Europe, Asia, and Australia. This highlights the worldwide interest in sustainable construction materials. The leading countries are often those with strong research institutions and funding for advanced materials research. The USA and China, for example, have numerous universities and research centers dedicated to materials science and engineering. Studies, such as those of Chen et al. (2020) [34], from prominent American institutions, and Wang et al. (2021) [35], from China, showcase the advanced research on the carbonation resistance of CSA cement and its implications for durability. These countries are at the forefront of research and innovation in sustainable construction materials. European countries, including Germany and the UK, have strong research programs in sustainable materials and construction engineering. Publications in leading journals such as Construction and Building Materials and Cement & Concrete Composites reflect the collaborative efforts in advancing sustainable construction practices. Additionally, studies from various countries like Belgium, Spain, Singapore, and Brazil underscore the importance of international collaboration in tackling global sustainability challenges.

The diversity of countries and publication trends involved in the research suggests a high level of international collaboration, and the research on CSA cement and its carbonation properties benefits from insights across different climatic conditions and construction practices. Figure 4 also reveals potential gaps in the research landscape. Countries with emerging construction industries but fewer publications may need more focus on developing sustainable materials like CSA cement.

4. CO_2 Interactions with Calcium SulphoAluminate Cement

Calcium sulphoaluminate (CSA) cement is increasingly recognized for its low carbon footprint and high early-age strength characteristics, making it a sustainable alternative to traditional portland cement. The research on CSA cement has gained momentum globally, focusing on its mechanical properties, durability, and environmental impact, particularly concerning CO_2 emissions and carbonation [17]. Early studies on CSA cement, particularly from China and the USA, have laid the foundation for understanding its unique properties and potential benefits. Zhang et al. (2009) [36] conducted extensive research on the carbonation resistance of CSA cement, demonstrating its superior performance compared to portland cement. Similarly, Pacheco Torgal et al. (2012) [9] highlighted the benefits of CSA cement in reducing CO_2 emissions during production, positioning it as a crucial material in the fight against climate change. The interaction of CSA cement with CO_2, particularly in terms of curing and long-term performance, has been the focus of several studies. This section explores the impact of CO_2 on CSA concrete, covering aspects such as strength, durability, mechanical properties, shrinkage, and environmental benefits.

4.1. Carbonation of CSA Binders

Carbonation occurs when CO_2 reacts with calcium hydroxide in concrete and leads to the sequestration of CO_2. This process, called carbonation-induced calcification, forms stable calcium carbonate that locks away CO_2 [37]. Carbonation can increase compressive strength, density, modulus of elasticity, and shrinkage properties of concrete, according to Achal and Mukherjee (2015) [38]. Conversely, Chen, Liu, and Yu (2018) [39] reported that carbonation can potentially reduce compressive strength and increase permeability, making concrete more susceptible to damage from water and chemical attacks.

Carbonation can lead to the breakdown of ettringite in CSA concrete, a mineral that causes expansion and cracking, potentially reducing its durability and strength [40]. Carbonation can also lead to the formation of carbonic acid, which can corrode steel reinforcement, causing a decrease in concrete strength [41]. Carbonation has also been shown to lower the pH of concrete, exposing it to chemical attacks and reducing the lifespan of concrete structures [42]. The effect of carbonation and acidic gases such as SO_2 and NO_2 is to lower concrete pH, leading to steel reinforcement corrosion below a pH of 9.5, with catastrophic corrosion occurring at pH levels below 7 [43].

Carbonation has different effects on alternative cements compared to portland cement. Unlike portland cement (PPC), where porosity decreases due to the formation of calcium carbonate (i.e., calcite) in the pores, carbonation of CSA binders increases concrete porosity by converting ettringite to gypsum, aluminum hydrocalcite, and calcite [25]. This process fills voids in the cement with $Ca(OH)_2$ crystals, enhancing concrete. Zhou and Glasser (2000) [44] studied carbonated synthetic ettringites and found that under certain conditions, hemihydrate can develop and then recrystallize to produce alumina, ferric oxide, and a monosulfate phase. Factors that affect the carbonation of CSA concretes include water–cement (w/c) ratio, pore structure, level of hydration, and relative humidity [45].

In a study on the carbonation of CSA mortars, Hargis et al. (2017) [46] investigated carbonation behavior, the microstructural and chemical factors that direct their rate of carbonation using w/c ratios of 0.65, 0.525, and 0.4. It was found that CSA mortars carbonate more rapidly than PPC mortars and at the same rate as calcium aluminate cement mortars. The anhydrite content of the CSA mortars strongly affected the ye'elimite reaction kinetics, which played an important part in imparting carbonation resistance in CSA mortars. It was noted that the reduction in the w/c ratio of CSA mortars slowed down their carbonation rate. These findings are important in understanding the carbonation behavior of CSA concrete and developing more durable and sustainable concrete mixtures.

Similarly, Fernandez-Carrasco et al. (2012) [47] investigated the carbonation rates of ternary cementitious materials including CSA under different conditions, including temperature, relative humidity, mix ratios, and 4% exposure to CO_2. It was discovered that carbonation rate was influenced by the type of cement used; carbonation rate also increased in CSA compared to PPC. It is difficult to conclude on the behavior of CSA under carbonation because of several factors as afore discussed. Geng et al. (2014) [48] noticed that the carbonation depth of sulphoaluminate cement concrete is lower compared to PPC irrespective of curing time. However, an accelerated carbonation laboratory study using 20% CO_2 and 70% relative humidity showed no significant change in carbonation depths between CSA and portland cement concrete mixes [26].

Studies have shown that the performance of CSA concrete exposed to increased CO_2 concentration is affected by numerous factors. For instance, in the study carried out by Leeman and Moro (2017) [45], there is a relationship between relative humidity, water–cement ratio and carbonation of CSA concrete. The strength of CSA concrete decreases as the CO_2 concentration increases only at a higher relative humidity (above 70%), and no significant difference was observed at 57% relative humidity. Similarly, Chen et al. (2016) also concluded that the porosity of the concrete increases with increased CO_2 concentration [39]. Moreover, T. Mi et al. (2023), upon investigating the corrosion process of reinforced concrete, realized that carbonation can lead to a decrease in the flexural strength and increase in the chloride ion permeability of the concrete [41]. Additionally, the carbonation process can impact the microstructure of concrete, leading to the formation of cracks and the breakdown of ettringite minerals [40]. Research has also shown that the impact of CO_2 concentration on the performance of CSA concrete is influenced by the type of curing used. For instance, Chen, Lui, and Yu (2018) [39] found that air-cured CSA concrete exposed to CO_2 concentration had a lower compressive strength compared to water-cured

CSA concrete exposed to the same conditions. The authors attributed this to the fact that the water-cured CSA concrete had a higher degree of hydration and lower porosity.

4.2. Shrinkage Property of CSA Concrete

One of the most remarkable properties of CSA cement is its shrinkage resistance. Shrinkage is the reduction in volume of concrete due to the loss of water or chemical changes in the cement paste [49]. Shrinkage-compensating concrete (SCC) is a type of concrete that compensates for drying shrinkage. Specifically, it is designed to minimize the tendency for cracking caused by drying shrinkage in concrete slabs, pavements, and structures. One of the key materials used in SCC is calcium sulphoaluminate (CSA) cement [50]. CSA concrete, using calcium sulphoaluminate cement as the main binder instead of the conventional portland cement, offers several advantages such as faster setting and hardening, higher early and ultimate strength, lower carbon footprint, and better durability [51]. CSA cement's unique hydration mechanism consumes water molecules during the formation of ettringite crystals, effectively eliminating excess bleed water and preventing drying shrinkage. Unlike ordinary portland cement, CSA cement contains no C_3A (tricalcium aluminate), which maximizes its sulfate resistance [52].

Several factors contribute to the shrinkage resistance of CSA concrete:

i. Water Demand and Chemical Binding: CSA cement requires more water than portland cement for proper hydration, but this water is chemically bound, causing no water surplus, and thus preventing shrinkage cracking and warping.
ii. Chemical and Stable Expansion: During the hardening phase, a chemical and stable expansion occurs that prevents further shrinkage over time.
iii. Low-Shrinkage Phases Formation: CSA cement forms phases such as calcium sulphoaluminate (C_4A_3S), ettringite ($C_6AS_3H_{32}$), and belite (C_2S), which have lower shrinkage potential than phases of portland cement such as alite (C_3S) and free lime (CaO) [53].

Studies have confirmed the shrinkage resistance of CSA concrete under different conditions and applications. Ke et al. (2018) [50] found that CSA concrete showed significantly lower shrinkage than portland cement concrete (PCC) in both sealed and unsealed conditions, as well as under drying and wetting cycles. Similarly, Zhang et al. (2016) [54] found that CSA concrete exhibited much less shrinkage than PCC under various temperatures and relative humidities, with relative humidity being the main influencing factor. Although CSA has proven effective as a shrinkage-compensating concrete, some studies have identified a critical relationship between the carbonation and shrinkage of CSA. Ye et al. (2017) [55] observed shrinkage performance of cement mortars containing various alkali salts at two different drying conditions (nitrogen gas and air); the results show that alkalis drastically increase shrinkage magnitude, but reduce the shrinkage kinetics of these mortars. The findings suggest that alkali enrichment could reduce creep modulus under drying-induced internal stress. Yuya et al. (2021) [56] also identified the relationship between carbonation shrinkage and the calcium/silicate ratio of C-S-H. The result shows that carbonation shrinkage progressively increased at intermediate relative humidities of 43% and 66%. These studies provide an idea of how carbonation can induce shrinkage in CSA concrete. They also highlight various factors such as concrete composition, environmental conditions, and the use of additives influencing this process. However, not many studies have investigated this, and the conclusion is subject to ongoing research.

4.3. Impact on Mechanical Properties

CSA has proven effective in applications requiring early strength and long-term strength [57]. For example, Markosian et al. (2019) [58] reported that CSA used on a prestressed bridge girder allowed the concrete to reach a strength of 4300 pounds per square foot (about 30 MPa) in only 6.5 h, demonstrating CSA's effectiveness for early strength applications. According to Jiaming Wang et al. (2022) [59], the impact of carbonation on the mechanical properties of concrete may vary depending on the type of cement being used.

For example, Ashraf et al. (2016) [60] and Zhang et al. (2024) [61] investigated the effect of CO_2 exposure on CSA cement-based mortars and found that exposure to CO_2 caused a reduction in the compressive strength and flexural strength of the mortars. The extent of the reduction depended on the percentage of CSA cement in the mix. SEM and XRD analysis revealed that the CO_2 exposure led to the formation of calcium carbonate, which caused the microstructure of the mortars to become more porous and less dense (see Figure 5). The authors also observed the formation of ettringite, which may have contributed to the reduction in strength.

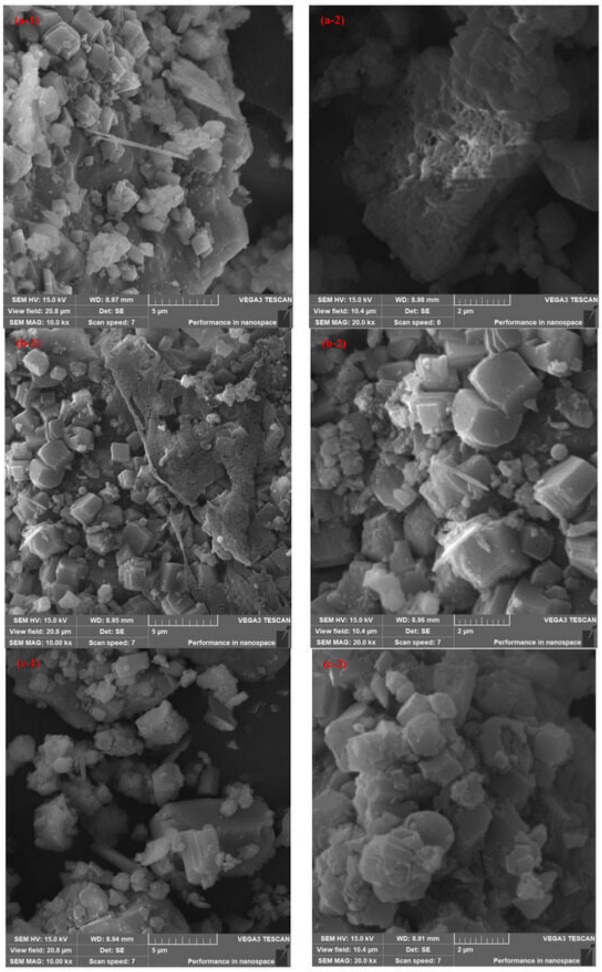


Image (a):

- *Magnification Level (SEM MAG): a-1: 10k, a-2: 20k*
- *Working Distance (WD): a-1: 8.97 mm, a-2: 8.98 mm*
- *View Field: 23.5 pt*
- *SEM Magnification (SEM MAG): a-1: 15.0 k, a-2: 8.34 µm*
- *Detector Type (Det): SE (Secondary Electron Detector)*

Image (b):

- *Magnification Level (SEM MAG): b-1: 10k, b-2: 20k*
- *Working Distance (WD): b-1: 8.95 mm, b-2: 8.36 mm*
- *View Field: 23.5 pt*
- *SEM Magnification (SEM MAG): a-1: 15.0 k, a-2: 8.34 µm*
- *Detector Type (Det): SE (Secondary Electron Detector)*

Image (c):

- *Magnification Level (SEM MAG): c-1: 10k, c-2: 20k*
- *Working Distance (WD): c-1: 8.94 mm, c-2: 8.91 mm*
- *View Field: 23.5 pt*
- *SEM Magnification (SEM MAG): a-1: 15.0 k, a-2: 8.34 µm*
- *Detector Type (Det): SE (Secondary Electron Detector)*

Figure 5. SEM images of carbonated CSA mortars [61].

Similarly, Sevelsted and Skibsted (2015) [62] investigated the effect of CO_2 exposure on the mechanical properties and durability of alkali-activated slag (AAS) mortars. The study found that CO_2 exposure caused a reduction in the compressive strength and increased water absorption of the AAS mortars. The extent of the reduction depended on the type of activator used. The formation of calcium carbonate and other phases in the microstructure of the AAS mortars was also observed, which can be similar to what happens in CSA concrete under CO_2 exposure. The study's findings on potential mitigation measures to improve the resistance of AAS materials to CO_2-induced degradation may also be applicable to CSA concrete.

In another study by Cao et al. (2022) [63] on the carbonation of reactive powder concrete with calcium sulphoaluminate cement, the authors found that the strength of the concrete increased upon carbonation after 7 days. However, it was noticed that the strength of the concrete began to decline after seven days before carbonation. Geng et al. (2014) [48] in their study on the carbonation of CSA cements also noticed something similar: that the compressive strength of CSA-based concrete initially decreased and later increased after prolonged exposure to CO_2, suggesting that carbonation can have complex effects on the mechanical properties of CSA concrete. The formation of a denser microstructure due to carbonation may contribute to the increase in the compressive strength of CSA concrete after longer exposure times to CO_2. However, the accelerated aging conditions used in the study may not fully reflect the long-term effects of CO_2 on CSA concrete. Therefore, further research is needed to better understand the impact of carbonation on the long-term durability of CSA concrete structures.

In a study by Groves et al. (1991) [64], experiments were conducted to investigate the changes in the phase composition, microstructure, and mechanical properties of CSA cement paste after CO_2 exposure. The results indicate that carbonation of CSA cement paste caused the formation of calcium carbonate and ettringite, which led to the degradation of the material's microstructure. The mechanical properties of the CSA cement paste were also affected by carbonation, with a decrease in compressive strength observed after exposure to CO_2. However, a counter argument in a recent study by Wang et al. (2021) [65] suggests that CSA concrete has good carbonation resistance and can even benefit from carbonation in terms of compressive strength. The authors found that the compressive strength of the CSA concrete increased after carbonation due to the formation of calcium carbonate in the pore structure, which helped to fill the pores and improve the mechanical properties. However, the authors also noted that attention needs to be paid to the impact on flexural strength and durability. The flexural strength and durability of the CSA concrete decreased after carbonation, possibly due to the formation of cracks in the interfacial transition zone between the cement paste and the aggregate.

To summarize, the effects of carbonation on the mechanical characteristics of concrete can be complicated and reliant on elements including the composition of concrete, the amount of exposure time, and the ambient conditions. Due to the production of calcium carbonate and other phases in the microstructure, exposure to CO_2 can generally reduce the compressive strength, flexural strength, and durability of concrete. By filling the pores and strengthening the microstructure, carbonation, according to some research, may enhance the compressive strength of specific types of cement, including CSA cement. Further investigation is required to comprehend the long-term impacts of carbonation on the mechanical characteristics of various types of cement and to develop mitigation techniques for carbonation's disadvantageous effects on the resilience of concrete structures.

4.4. Impact on Carbonation Depth

Carbonation depth is the extent to which CO_2 penetrates the concrete, and it can vary depending on factors such as the concrete composition, exposure conditions, and permeability. The depth of carbonation can affect the extent of chemical changes in the concrete and its mechanical properties [66]. Geng et al. (2014) [48] noticed that the carbonation depth of concretes made with CSA cement increases with an increased exposure time to

CO_2, leading to more exposure in the pore structure of the concrete. This indicates that carbonation can be a potential durability concern for CSA concrete structures. Wang et al. (2021) [65] provides key insights into the impact of carbonation on the microstructure and mechanical properties of concrete, specifically in relation to fiber-reinforced concrete (FRC). The study presents experimental results showing that the carbonation depth of FRC is lower than that of conventional concrete, and that the carbonation reduces the porosity and interfacial transition zone thickness of the FRC, resulting in improved compressive strength and modulus of elasticity. The study also highlights the role of fibers in enhancing the resistance of FRC to carbonation-induced deterioration. This study explains that carbonation can impact the properties of CSA concrete, and fiber reinforcement may play a role in mitigating these effects.

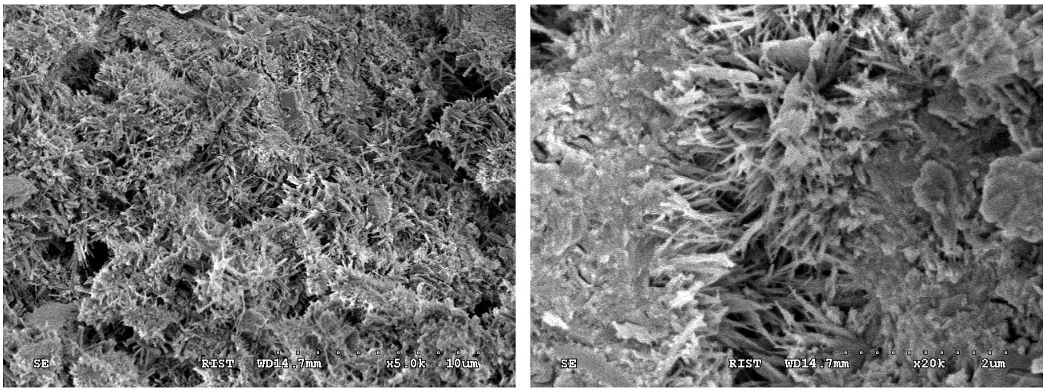
Zhang et al. (2009) [36] investigated the effect of w/c ratio and admixtures on the carbonation resistance of sulphoaluminate cement-based high-performance concrete (HPC). The experimental results indicated that decreasing the w/c ratio leads to a significant decrease in carbonation depth and an improvement in carbonation resistance. The addition of slag and fly ash in the ratio 2:1 also enhanced the carbonation resistance of the concrete. In another study, Duan et al. (2013) [67] examined the addition of magnesium aluminate-based layered double hydroxides (LDHs) to sulphoaluminate concrete. This led to a significant decrease in carbonation depth, indicating improved carbonation resistance. It was also found out that the carbonation depth of CSA concretes is less compared to portland cement concrete irrespective of the addition of LDHs. This suggests that CSA concretes may have higher carbonation resistance compared to PC concretes.

Ultimately, carbonation can have a significant impact on how long concrete will last and how it will behave mechanically, including CSA cement-based concrete. Reducing the w/c ratio and adding admixtures can improve the carbonation resistance of concrete. The depth of carbonation can vary depending on several factors, including the concrete composition and exposure conditions. Concrete qualities like compressive strength and modulus of elasticity can be less negatively affected by carbonation by adding fiber reinforcement and LDHs based on magnesium aluminate. In comparison to portland cement concretes, CSA concretes may have stronger carbonation resistance, which suggests a possible advantage of CSA concrete structures in terms of durability over portland cement concrete structures.

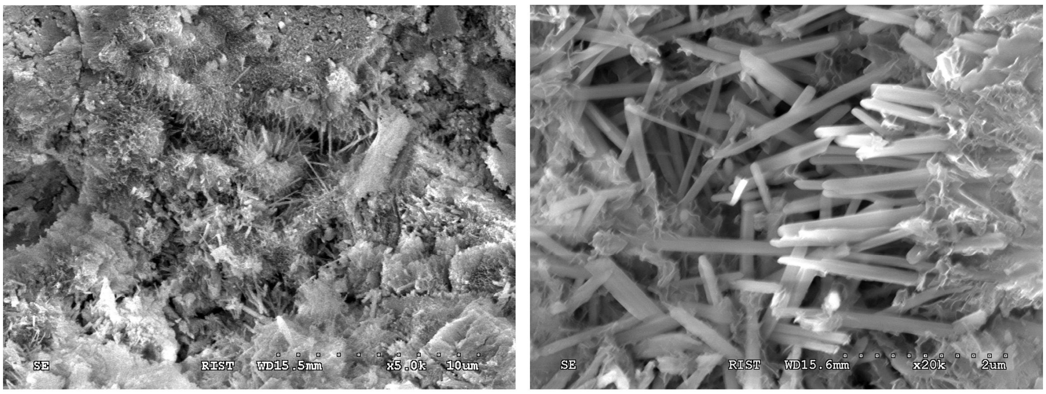
4.5. Impact on Chemical Properties of Concrete

Carbonation in concrete, a chemical reaction that leads to the formation of calcium carbonate ($CaCO_3$), significantly impacts the chemical properties of CSA concrete [68]. This process is influenced by the concrete's porosity and moisture content, and it occurs under specific conditions of relative humidity (RH) levels between 40% and 90%. The carbonation process involves three stages: CO_2 reacts with water to produce carbonic acid; dissolved calcium ions react with carbonic acid to produce trioxocarbonate; and finally, $CaCO_3$ precipitates, reducing calcium ions in the solution [69].

Sharma et al. (2023) [29] found that carbonation curing influenced the microstructural characteristics and CO_2 uptake of CSA cement. The low-pH carbonic acid promoted ettringite participation in $CaCO_3$ formation, leading to the formation of different $CaCO_3$ polymorphs, $Al(OH)_3$, and unreacted ye'elimite. The dissolution of hydrated phases moderately affected the strength of the concrete. The study suggests CO_2 can impact the chemical properties of CSA concrete. Taylor et al. (2001) [70] examined the effects of carbonation on CSA cement and found that it can lead to a loss of strength due to the breakdown of ettringite into aluminum hydroxide, gypsum, and calcium carbonate. This reaction is highly sensitive to carbonation, indicating a significant impact on the concrete's chemical properties. Similarly, Zhang et al. (2009) [36] and Cho et al. (2017) [71], using SEM and XRD analysis (see Figure 6), found that ettringite, the main hydration product of sulphoaluminate cement, decomposes after carbonation, leading to a loss of strength in CSA concretes. However, Ansari et al. (2022) [28] proposed a new binder (MCSA) by replacing 20% of CSA with fine cement-sands, which was found to improve the mechanical properties and resistance to carbonation in CSA concretes. These findings suggest the need for further research to develop new materials and techniques to mitigate the negative impact of carbonation on the chemical properties and strength of CSA concrete.



(a) O50B30G20



(b) O50B30AS10G10

Figure 6. SEM images showing ettringite formation [71].

In a recent study by Wang et al. (2021) [65], the impact of carbonation on the chemical properties of CSA cement was investigated. The authors found that carbonation resulted in the formation of calcium carbonate ($CaCO_3$) and the breakdown of ettringite, leading to a reduction in the compressive strength of the cement. Specifically, carbonation caused the decomposition of ettringite into gypsum and calcium carbonate. The authors also found that the carbonation rate of CSA cement was affected by factors such as relative humidity, temperature, and exposure time to CO_2. The study highlights the importance of considering the impact of carbonation on the chemical properties of CSA concrete, particularly in applications where durability and strength are critical factors. In Duan et al. (2013)'s [67] study on how the addition of magnesium aluminate-based layered double hydroxides (LDHs) to CSA cement affects its behavior, it was found out that the LDHs affected the pore structure of the concrete made with calcium aluminate cement, and the exchange and immobilization of carbonate ions is believed to have contributed to the enhanced carbonation resistance.

Gastaldi et al. (2018) [72] explored the effect of carbonation on the microstructure and composition of CSA concrete and compares it to that of ordinary portland cement (OPC) concrete. The study's findings reveal that the carbonation of CSA concrete led to a decrease in pH, a reduction in the amount of calcium hydroxide (CH), and the formation of $CaCO_3$. These changes were like those observed in OPC concrete but occurred at a faster rate in CSA concrete. Also, the study found that the carbonation of CSA concrete decreased the amount of ettringite, a primary hydration product in CSA cement. Moreover, the study found that the carbonation of CSA concrete led to the formation of two distinct layers of $CaCO_3$. The inner layer, formed near the surface of the aggregate particles, was composed of dense and fine-grained $CaCO_3$ crystals. The outer layer, formed in the cement paste, was composed of coarser and more porous $CaCO_3$ crystals. These layers bring about increased porosity in the concrete, which may have contributed to the observed strength decline. Overall, these findings suggest carbonation can significantly impact the chemical properties of CSA concrete, including changes in pH, reduction in CH, and the formation of $CaCO_3$ and ettringite depletion. These chemical and microstructural changes may ultimately lead to a decrease in the strength and durability of CSA concrete.

Quillin (2001) [73] concluded that the chemical properties of CSA concrete are significantly influenced by exposure to CO_2. The author found that the carbonation process in CSA concrete leads to the dissolution of the ettringite phase, resulting in a decrease in pH and an increase in porosity, which leads to a decrease in the compressive strength of the concrete. Furthermore, the author noticed that the extent of carbonation depends on the composition of the concrete mix, with mixes containing higher levels of C_3A being more susceptible to carbonation. According to Fernandez-Carrasco et al. (2012) [47], $Al(OH)_2$ was noticed from the XRD experiment for all the samples tested at early age. However, after 90 days, $Al(OH)_2$ was only noticed in the calcium aluminate samples. The study concluded that carbonation impacts the evolution of the hydrated phases of ternary cements, which tends towards the formation of calcium carbonate, gypsum, and aluminum hydroxide as discussed in prior studies.

In another study, L. Wang et al. (2019) [74] explored the pore solution chemistry of CSA cement and how it impacts steel passivation. The results from the investigation showed that the pore solution of CSA cement had a notably lower pH and increased aluminum and sulfate ion concentrations when compared with ordinary portland cement. It was noticed that the high sulfate concentration leads to the formation of gypsum and ettringite, which can impact the corrosion resistance of steel rebars in concrete. The study also discovered that the addition of silica fume to CSA cement in concrete mix can raise the pH and reduce the sulfate concentration, which can lead to enhanced steel passivation. Carbonation of CSA can also affect the passivation of steel because of the lowered pH, which is also particularly important in understanding the durability of concretes made from CSA cement. It is therefore important to understand the pore solution chemistry of CSA cement. The authors also identified how $Al(OH)_4{}^-$ can potentially provide protection to steel because of its ability to release hydroxyl during the reactions. The chemical process is presented below:

$$Fe^{2+} + 2H_2O = Fe(OH)_2 + 2H^+$$
$$Al(OH)_4{}^- \leftrightarrows Al\,(OH)_3 + OH^- \quad (1)$$

In summary, substantial research has been conducted on the effects of carbonation on the chemical characteristics of concrete, especially in CSA cement. The breakdown of ettringite and the generation of calcium carbonate ($CaCO_3$) because of carbonation might cause the concrete's compressive strength to decrease. Many variables, such as temperature, relative humidity, exposure duration to CO_2, and concrete mix composition, have an impact on the carbonation rate. The chemical and microstructural alterations brought on by carbonation may eventually cause CSA concrete's strength and durability to decline. New binders and additives have been suggested by certain research to improve CSA concrete's resistance to carbonation. Further research is required to develop novel materials and techniques to mitigate the negative impact of carbonation on the chemical properties and strength of CSA concrete.

4.6. Environmental Impact

The impact of CO_2 on CSA concrete is not only limited to its mechanical properties but can also have environmental implications, as the production of CSA concrete can contribute to carbon emissions and climate change [75]. Mechling et al. (2014) [24]

highlights the sensitivity of CSA cement mortars to carbonation, which can lead to changes in their mechanical properties and dimensional stability. This information can be used to emphasize the importance of considering the effects of carbonation on the long-term durability and performance of CSA concrete in different environmental conditions. Additionally, the paper highlights the advantages of CSA cement over OPC in terms of energy use and carbon dioxide generation during manufacture, which can be useful in discussing the potential benefits of using CSA concrete as a more sustainable alternative to traditional cementitious materials.

Similarly, Zhang et al. (2009) [36] investigated the impact of CO_2 on the durability of CSA concrete under different environmental conditions, with samples exposed to CO_2 for 7, 14, 28, and 56 days. The results show that the carbonation depth of CSA concrete increases significantly with exposure time, and the carbonation depth is higher in a CO_2-rich environment compared to a normal air environment. The study also suggests that the carbonation of CSA concrete is accelerated in a high humidity and high-temperature environment. Therefore, the study suggests that the durability of CSA concrete should be evaluated by considering the carbonation resistance in different environmental conditions. Vu et al. (2019) [27] also studied the impact of climatic conditions on the carbonation depth of various kinds of concretes under sheltered and unsheltered situations over a five-year period. The results indicate that the general carbonation trend was not much different irrespective of the macroclimate. However, the number of rainy days had a more considerable influence on the progress of carbonation than the total rainfall in the region. This could explain how CSA concrete would perform under similar conditions, since the compositions of the materials tested have similar characteristics.

In another study, Hargis et al. (2017) [46] noticed that portland cement had a greater CO_2 binding capacity than CSA cement, with result disparities of 50 and 19.2. This could suggest that portland cement may be a better option than CSA cement in terms of reducing carbon emissions associated with concrete production. However, this is a subjective statement based on the context of application. Further studies are needed to better understand the carbon footprint of both concrete made from PC and CSA, especially from a cradle-to-grave point of view.

It can be concluded that the carbonation depth of CSA concrete is influenced by climatic conditions. The results show that the general trend of carbonation in CSA concrete is not much different irrespective of the macroclimate, but the number of rainy days has a more considerable influence on the progress of carbonation than the total regional rainfall as presented by [27]. In addition, sheltering the concrete specimens had a significant effect on reducing carbonation. Recent studies, however, suggest that careful consideration should be given to the environmental exposure of CSA concrete structures to minimize the risk of carbonation-induced damage.

4.7. Mitigation Strategies for Carbonation of CSA Concrete

Various mitigation strategies have been proposed to reduce the negative impact of carbonation on CSA concrete. One such strategy is the use of supplementary cementitious materials (SCMs) in the concrete mix. SCMs such as fly ash, slag, and silica fume have been found to reduce the porosity of concrete, leading to reduced carbonation [45]. Also, corrosion inhibitors, such as calcium nitrite, and organic inhibitors have been proposed to reduce the corrosion of steel reinforcement caused by carbonation [41].

Another strategy is the use of coatings or sealers on the surface of the concrete to reduce the ingress of CO_2 and other harmful gases, as described in the work of Chen, Lui, and Yu (2018) [39]. Another study recommended the use of lower w/c ratios in the concrete mix, which can also reduce the porosity of the concrete and limit the extent of carbonation [76]. Based on the findings by Duan et al. (2013) [67], the addition of magnesium aluminate-based layered double hydroxides (LDHs) to CSA concrete improved its carbonation resistance significantly. This was attributed to the modification of the pore structure of the concrete, which reduced the available space for CO_2 to penetrate and react with the cement phases. The LDHs were also found to immobilize carbonate ions, preventing them from reacting with the cement phases. Therefore, incorporating LDHs in CSA concrete could be a promising approach to address the challenges with pore structure and improve the carbonation resistance of CSA concrete. The study by Cho et al. (2017) [71] provides a promising approach by using industrial byproducts like aluminum-rich slag and ground granulated blast furnace slag. These can reduce the carbon footprint by minimizing the need for OPC, which is energy-intensive to produce. The formation of stable hydrates and an improved microstructure also contributes to the durability and longevity of the concrete, further reducing CO_2 emissions over its lifecycle.

In summary, the reviews suggest that carbonation is a complex process that can impact the performance and durability of CSA concrete. While carbonation can have some beneficial effects, such as increased strength and density, it can also lead to a decrease in the long-term strength and durability of the concrete. Consequently, it is important to understand the factors that influence carbonation and to develop effective mitigation strategies to enhance the acceptance of CSA concrete.

Overall, there are many ways that CO_2 has an impact on CSA concrete. It is evident that carbonation can significantly impact the long-term performance of concrete, despite it affecting both the strength and durability of the concrete negatively and positively. According to previous studies, carbonation can cause ettringite minerals to break down, increase porosity, increase chloride ion permeability, and reduce compressive and flexural strength. To increase the adoption of CSA concrete, it is crucial to create efficient mitigating techniques.

Thankfully, studies have shown that there are several ways to lessen the impact of CSA concrete production on the environment and restrict the harmful effects of carbonation. They include the use of corrosion inhibitors, additional cementitious materials, and alternative cementitious materials, as well as carbon capture and storage technologies. Moreover, applying coatings or sealants to the concrete's surface and using less water and cement in the concrete mix can help restrict the amount of carbonation and limit the entry of dangerous gases.

4.8. Summary of Some Studies on CSA Concrete

Some of the studies critically examined for the qualitative analysis are highlighted in following table. The table includes the title of each study, the key findings relating to CSA carbonation and the novelty of each study. This was done to provide transparency and an overview of the studies identified. Additionally, this summary helps to compare novelties and methodologies in different studies to identify trends, gaps, and areas where further research is needed.

Author(s)	Study Title	Findings	Novelty
[28]	A novel approach to improve carbonation resistance of Calcium SulfoAluminate cement by assimilating fine cement-sand mix.	CSA could be more resistant to carbonation with partial replacement of CSA cement with fine particles. Modified CSA samples with fine-cement sand mix showed an over 12% increase in compressive strength upon carbonation as compared to OPC and CSA.	The study proposes an enhanced cement formulation (OMCSA) to reduce carbonation of CSA. It also addresses the main barriers of carbonation in CSA cement by partial replacement with CSA < 2.4 µm powder and shows that mixing OPC or conventional CSA with fine CSA < 2.4 µm cement mortar to various proportions is a viable way to mitigate this issue.

Author(s)	Study Title	Findings	Novelty
[24]	SulfoAluminate cement behaviors in carbon dioxide, warm and moist environments	CSA mortar is highly sensitive to carbonation. Increased water content reduces the mechanical properties and dimensional stability of CSA concrete.	The authors propose a set of mortars at 3 w/c ratios to test the material's performance under different conditions. The study also compares CSA mortars with CEM I portland cement mortars. In addition, the behavior of calcium sulphoaluminate cements in four different environments (ambient air @20 °C and 65% RH, dry air @45 °C and 35% RH, water @45 °C, saturated CO_2 @20 °C) were compared.
[39]	Effects of Environmental Factors on Concrete Carbonation Depth and Compressive Strength	Found out that concrete has three stages of carbonation, each of which corresponds to the presence of different polymorphs.	The authors propose a relationship between concrete carbonation and temperature, CO_2 concentration, and humidity based on XRD, ESEM, and SEM. A novel model to predict carbonation depth and compressive strength in concrete is also proposed.
[60]	Carbonation of cement-based materials: Challenges and opportunities	Noticed that concrete using OPC as the primary binder had a stronger carbonation resistance than concrete with SCMs (such as silica fume, slag, or fly ash) or alternative binder ingredients (i.e., C_2S, AAM). Carbonation has historically been seen as a negative factor for cement-based materials. However, it can also be seen as a chance to develop a CO_2-efficient concrete industry by storing CO_2 in cement-based materials and using carbonate binders.	The study reviews progress in carbonation of cement-based materials by extracting concrete highlights from peer-reviewed journals. In addition to the existing knowledge regarding the carbonation of cement-based materials, areas that require further research are also identified.
[16]	Durability and microstructure of CSA cement-based materials from MSWI fly ash.	Researched the use of fly ash as a raw material for cement. Used MSWI fly ash as a raw material to prepare new type of cement, which was called CSA cement. Successfully used MSWI fly ash as raw material to prepare lime-free sintering cement.	The study explored MSWI fly ash as cementitious material for sustainable construction. It proposes a novel method of MSWI fly ash being transformed into cement that results in durable and effective material that exceeds current global limits for heavy metal leaching. The study also used MSWI fly ash in cement, with hydrated alkali solutions and biomaterials to produce new mortar and building blocks.
[77]	CSA-based portland-free binders to manufacture sustainable concretes for jointless slabs on ground.	The paper explored the possibility of manufacturing eco-friendly shrinkage-compensating mortars by using CSA-based ternary mixtures to replace OPC with SCMs and lime (CH). Replacing OPC with SCM and lime can potentially reduce CO_2 emission and energy consumption by up to 60 percent.	The paper evaluates the impact of water/binder ratio, condition of curing, and tartaric acid dosage on elastic, rheological, and physical properties of CSA concretes, SCM, and anhydride concretes that have shrinkage-compensating properties.

Author(s)	Study Title	Findings	Novelty
[17]	Recent progress and technical challenges in using calcium sulfoAluminate (CSA) cement.	Found out that CSA cement can be used as a replacement for portland cement to reduce CO_2 emissions. The study introduces the hydration mechanism, long-term durability, and new applications of cement made from the CSA minerals.	Profiles CSA cement with respect to its hydration mechanism, mechanical properties, and long-term durability. The study reviewed the literature on the hydration mechanisms of CSA cement and the properties of its hardened cement paste, including strength, durability, and chemical composition. It discussed recent work and potential challenges associated with producing CSA cement at an industrial scale. The potential applications of CSA cement in developing infrastructure in regions where fresh water is scarce was also explored.
[78]	Novel use of calcium sulfoAluminate (CSA) cement for treating problematic soils	The study noticed that using CSA cement in clay-based ground stabilization solutions was more environmentally sustainable than using lime or cement. Identified CSA cement as a sustainable alternative in porous aggregates stabilization. Found out that CSA cement-treated expansive soil exhibited three distinct hydration phases, where the state of hydration was identified through experimentation.	The authors explored a sustainable approach to cement replacement by investigating the effectiveness of CSA cement in ground stabilization. The study proposes CSA cement as an alternative for expansive soil stabilization due to reduced carbon impact. Hydration of CSA cement into expansive soil and its effect on mechanical properties and microstructural change was investigated. The cationic exchange, flocculation, and agglomeration characteristics of CSA cement in expansive soil was also investigated.
[79]	Behavior of blends of CSA and portland cements in high chloride environment	The study achieved high early strength of CSA cement composite in high chloride environments. CSA was found to be effective in showing high mechanical performance even in high chloride conditions. CSA binders could also prove resistant to chloride attack.	Describes a novel approach to cement mix design that uses multi-objective optimization to maximize early strengths and durability in marine environments. The study addressed the durability aspects of CSA cement in concrete. Proposes concrete with CSA replacing some of the OPC in different proportions, suitable for marine environments where seawater interacts with concrete.
[80]	Decomposition of synthesized ettringite by carbonation	The study showed that the carbonation mechanism is different under wet and dry conditions. This can be explained by the excess or lack of water around or in the ettringite. It was discovered that ettringite can capture CO_2 and produce stable solid mineral products.	The authors proposed a theoretical model of carbonation kinetics based on ettringite and its reaction with CO_2 gas. The theoretical model was used to predict carbonation rates using the Jander equation. Proposes a realistic and powerful model for long-term geological sequestration of CO_2.

Author(s)	Study Title	Findings	Novelty
[81]	Cement-based materials eventually reabsorb much of the CO_2 released during creation.	Concrete re-absorbs about 43% of the CO_2 emitted during cement production over its life cycle.	Discovered that concrete reabsorbs a significant amount of the CO_2 emitted during cement production.
[82]	Effects of CSH2 and CH on Strength and Hydration of Calcium SulphoAluminate Cement Prepared from Phosphogypsum	Phosphogypsum increases the strength performance of CSA concrete. The pH of samples increased with the addition of CH. The paper found that adding gypsum dihydrate and calcium hydroxide to cement clinker prepared from phosphogypsum affects the compressive strength and hydration process of the cement.	Investigation of carbonation of CSA with varying w/c ratio. The intervention of optimizing the use of mineral admixtures such as gypsum dihydrate and calcium hydroxide to cement clinker prepared from phosphogypsum.
[63]	Research into Carbon Dioxide Curing's Effects on the Properties of Reactive Powder Concrete with Assembly Unit of SulphoAluminate Cement and Ordinary portland Cement	The findings of the paper are that the addition of sulphoaluminate cement can improve the mechanical strength of RPC at low curing age, but when the curing age is beyond 7 days, the sulphoaluminate cement has a negative effect on the mechanical strength. CO_2 curing increases the mechanical strength and the resistance of RPC to sodium chloride (NaCl) freeze–thaw cycles.	The paper examines the effects of carbon dioxide curing on the properties of reactive powder concrete with assembly unit of sulphoaluminate cement and ordinary portland cement. This study uses a combination of rapid-setting sulphoaluminate cement, OPC, and silica fume as one kind of mineral admixture.
[76]	Durability of calcium sulfoAluminate cement concrete	The paper suggests that CSA concrete has better performance than portland cement concrete in several aspects, including shrinkage and cracking due to restrained shrinkage, freeze–thaw damage, alkali–silica reaction, and sulfate attack.	Reviewed durability of CSA concretes in general.
[45]	Carbonation of concrete: the role of CO_2 concentration, relative humidity, and CO_2 buffer capacity	The carbonation coefficients determined at the different relative humidities (RH) of 57, 70, and 80% clearly indicate that the response of a concrete to carbonation at increased RH is both dependent on cement type and w/c. The carbonation resistance of concrete in sheltered and with restrictions in unsheltered outdoor exposure can be assessed at 4% CO_2 and 57% RH.	The effect of CO_2 concentration and ambient relative humidity (RH) on the accelerated and natural carbonation of eighteen concrete mixtures produced with nine different cement types was studied over days.

Author(s)	Study Title	Findings	Novelty
[74]	Pore Solution Chemistry of Calcium Sulfoaluminate Cement and Its Effects on Steel Passivation.	The pore solution chemistry of CSA can affect the passivation of steel reinforcement, which can have implications for the durability and long-term performance of concrete structures. The study identified a novel ion ($Al(OH)_4^-$) in CSA pore solution, which is not present in OPC. The study found that CSA pore solution chemistry can promote the formation of a protective layer on the steel surface, which can help to prevent corrosion. However, the study also found that certain ions in the pore solution, such as chloride ions, can negatively impact steel passivation and promote corrosion. This highlights the importance of carefully managing the chemistry of the pore solution in CSA concrete to ensure the long-term durability of concrete structures.	The study investigates the effects of CSA cement on the passivation of steel, which has not been extensively studied in previous research. The study also explores the pore solution chemistry of CSA cement, providing insights into the mechanisms by which the cement impacts steel corrosion. Additionally, the study suggests that the use of CSA cement may offer an eco-friendlier alternative to traditional portland cement due to its lower carbon footprint.
[46]	Carbonation of calcium sulfoaluminate mortars	Found that CSA mortars carbonate faster than portland cement mortars and at the same rate as calcium aluminate cement (CAC) mortars. The anhydrite content of the CSA mortars strongly affects the ye'elimite reaction kinetics, which play a vital role in imparting carbonation resistance in CSA mortars. CSA mortars carbonate slower with decreasing water content. Calcium sulfate additions to CSA clinker to produce CSA cement dilutes the clinker content and reduces the amount of CO_2 that the CSA cement can bind. Thermodynamic modeling can be used to predict the carbonation process of CSA mortars.	This study provides a comprehensive investigation of the carbonation process in CSA mortars, including the physical and chemical parameters that govern the carbonation rate and the microstructural and chemical factors that affect the rate of carbonation in CSA cement. Additionally, it also presents a detailed analysis of the part anhydrite content and calcium sulfate additions play in the carbonation resistance of CSA mortars. Finally, it provides thermodynamic modeling to support the experimental results and to better understand the carbonation process in CSA cement. The study gives comprehensive insight to the behavior of CSA cement under carbonation and gives suggestions on how to improve the durability of CSA.

Author(s)	Study Title	Findings	Novelty
[67]	Influence of layered double hydroxides on microstructure and carbonation resistance of sulphoAluminate cement concrete	The addition of magnesium aluminate-based layered double hydroxides (LDH) to CSA concrete improves its carbonation resistance significantly. The LDHs modify the pore structure of the concrete, reducing the amount of available space for CO_2 to penetrate and react with the cement phases. The LDHs can immobilize carbonate ions, preventing them from reacting with the cement phases. The use of fly ash in the concrete mixture further improves the carbonation resistance of the CSA concrete, resulting in a lesser carbonation depth compared to portland cement concrete.	The use of magnesium aluminate-based layered double hydroxides (LDHs) as an additive to improve the carbonation resistance of sulphoaluminate cement (SAC) concrete. Previous studies have focused on the use of various materials to improve the performance of portland cement-based concrete, but this study specifically focuses on SAC concrete, which has different properties and composition. The study also characterizes the effects of LDHs on the pore structure of the concrete using mercury intrusion porosimetry (MIP), which is a technique not commonly used in studies on concrete carbonation resistance. The finding that the addition of LDHs can significantly improve the carbonation resistance of SAC concrete by modifying its pore structure and immobilizing carbonate ions is also novel and contributes to the development of more sustainable and durable concrete materials.
[47]	Carbonation of ternary building cementing materials	The carbonation resistance of ternary building cement materials is higher than that of pure portland cement. The carbonation resistance of the cementing materials increases with the increase in fly ash and limestone powder content. The carbonation depth of the cementing materials decreases as the curing time increases, indicating that the carbonation reaction is a slow process. The C-S-H in the cementing materials are more stable than the CH phase during the carbonation process, which contributes to the carbonation resistance of the materials. The formation of $CaCO_3$ during the carbonation process aids the decrease in porosity and the improvement in the mechanical properties of the cementing materials.	The study investigates the carbonation behavior of ternary cementitious materials, which are composed of different combinations of portland cement, calcium aluminate cement, and calcium sulphoaluminate cement. This study's objective was to provide a comprehensive understanding of the behavior of ternary cements under carbonation, which can potentially lead to the development of more sustainable and durable building materials. Additionally, the use of different techniques such as XRD and thermogravimetric analysis allowed for a detailed characterization of the reaction products and the carbonation process.

Author(s)	Study Title	Findings	Novelty
[65]	Mechanical and Microstructural Characteristics of Calcium Sulfoaluminate Cement Exposed to Early-Age Carbonation Curing	CSA cement pastes' compressive strength increased with briquetting pressure. However, the relationship is not linear; the growth rate of the compressive strength slows down with increasing briquetting pressure. At briquetting pressure less than 20 MPa, the compressive strength of the test block at 3 days does not differ much from the strength at 1 day. When the briquetting pressure exceeds 20 MPa, the gap between the strength at 1 day and 3 days gradually increases. The water/binder ratio also impacts the compressive strength of the cement paste. When the water/binder ratio is 0.05, the compressive strength of the test block after carbonation curing becomes very low. The optimal starting point for carbonation curing is 4 h after the start of hydration. The compressive strengths after carbonation curing are all above 50 MPa, while the strength of the specimens only reaches 37 MPa after 3 days of standard curing. This shows that early-age carbonation curing can greatly improve the early mechanical properties of CSA cement paste. As the carbonation curing starting point progresses, the strength of the specimens after carbonation curing showed a tendency to decrease rather than increase. The occurrence of the carbonization reaction can promote the hydration of the cement paste. As the hydration progresses, the paste becomes denser and the porosity becomes lower, so it is increasingly difficult for CO_2 to diffuse into the paste. When carbonization is carried out at the early stage of hydration, the CO_2 diffuses more easily into the paste, and the hydration and carbonization reactions proceed simultaneously and mutually reinforce each other, thus significantly increasing the compressive strength of the specimen.	The paper discusses the physicochemical reactions that occur during early accelerated carbonization, including phase transition and mass transfer of CO_2, dissolution of solid $Ca(OH)_2$ and mass transfer of dissolved $Ca(OH)_2$, hydration of cement compounds, and carbonation of unhydrated cement compounds and hydration products. The authors note that while there are similar studies on other types of cement and concrete materials, there are relatively few studies on the performance of early carbonation curing of CSA cement. The paper also presents a comprehensive analysis of the hydration carbonization reaction of minerals in the CSA cement paste, indicating that the earlier the carbonation starting point is, the more favorable it is for the reaction. It was also noted that different carbonation starting points will not change the types of carbonization reaction and hydration reaction products but will affect the degree of reaction and macroscopic performance.

5. Analysis of CO_2 Impact on CSA Concrete

This study reviews the impact of CO_2 on concretes made from calcium sulphoaluminate (CSA) cements, highlighting their potential as a sustainable alternative to portland cement in terms of reduced carbon emissions [17,46]. Previous research indicates that CSA concrete exhibits other noteworthy properties, including rapid setting, lower energy consumption, and self-stressing properties [83]. Studies such as [24,27] highlight the high sensitivity of CSA cement mortars to CO_2 environments, showing significant variations in performance based on CO_2 exposure. These works demonstrate that CO_2 curing can improve early strength, but may influence long-term durability. Additionally, the results indicate that CO_2 curing accelerates the hydration process, leading to rapid strength gain. However, this process also introduces complexities in long-term stability that require further investigation. In another study by Honfei Cao et al. (2022) [63], CO_2 curing was found to significantly reduce the shrinkage property of CSA concrete. The study highlights that the carbonation process contributes to the formation of stable phases that limit volume changes. The reduced shrinkage observed together with enhanced durability under CO_2 exposure make CSA concrete a promising material for applications requiring long-term dimensional stability.

Sirtoli et al.'s (2015) [84] study finds CSA cement as an eco-friendly alternative, demonstrating significant mechanical benefits when exposed to CO_2. The cement showed improved compressive strength and reduced environmental impact due to lower CO_2 emissions during production. The mechanical properties under CO_2 curing conditions were notably enhanced, suggesting potential for rapid repair applications in concrete structures. The study by Tan et al. (2020) [76] suggests that CSA concrete performs better compared to traditional cements in CO_2-rich environments, showing resistance to carbonation and improved durability. However, the consensus on long-term performance is not definitive. This underscores the need for comprehensive studies to evaluate the long-term effects of CO_2 exposure on CSA concrete, particularly under varying environmental conditions. In Tan et al.'s (2020) [76] study, the durability of CSA cement was confirmed with improved performance in CO_2 environments compared to ordinary portland cement. The carbonation process contributes positively to the material's resistance against environmental degradation. This also emphasizes the CSA's suitability for use in infrastructures exposed to CO_2, such as pavements and underground structures, where natural carbonation could be leveraged to improve concrete performance.

However, a comprehensive understanding of parameters such as corrosion resistance, expansion mechanisms, and durability concerns is still needed [76]. The reviewed literature suggests that while CSA concrete offers significant advantages, it also presents challenges, particularly related to carbonation and its effects on mechanical properties and long-term durability. Studies show that CSA cement mortars are susceptible to rapid carbonation, which impacts their dimensional stability and mechanical properties [24]. Carbonation curing can increase CO_2 uptake capacity, with a maximum four-fold increase observed at increased w/c ratios [29]. While carbonation can improve mechanical strength and resistance to NaCl freeze–thaw cycles in reactive powder concrete containing CSA cement [63], it may also lead to strength reduction in pure CSA binders due to increased pore volume [85]. The carbonation process in CSA cement involves the formation of calcium carbonate polymorphs, $Al(OH)_3$, and unreacted ye'elimite, which is different from traditional portland cement carbonation [29].

Calcium sulphoaluminate (CSA) cement is complex, and its performance is not fully understood. No specific conclusions have been reached regarding the durability of this binder compared to portland cement. However, due to its composition and inherent qualities, CSA concrete is expected to outperform portland cement concrete in several areas, including shrinkage properties, cracking, freeze–thaw resistance, alkali–silica reaction, and sulfate attack [76]. These findings highlight the complex relationship between CO_2 and CSA cement, emphasizing the need for further research on its long-term durability and performance.

A critical analysis reveals that although some studies report decreased compressive and flexural strength upon carbonation, others suggest improvements in certain conditions. The reliability and validity of these studies vary, with differences in study designs, sample sizes, and experimental conditions impacting their conclusions. Connecting these findings to broader sustainability goals, CSA concrete's reduced carbon footprint and potential for carbon sequestration through carbonation highlight its role in sustainable construction practices. However, effective mitigation strategies for carbonation's detrimental effects are crucial for its broader adoption.

6. Conclusions

The comprehensive review of the literature on the impact of CO_2 on calcium sulphoaluminate (CSA) concrete underscores its significant potential as a sustainable alternative to ordinary portland cement (OPC). CSA concrete offers notable advantages, including lower CO_2 emissions during production, rapid setting times, and enhanced durability under certain conditions. However, the review also highlights critical challenges, particularly related to carbonation.

The study revealed that carbonation's impact on CSA concrete is multifaceted, influencing its mechanical properties, durability, and chemical stability. While CSA concrete shows improved early-age strength and resistance to environmental degradation, its susceptibility to carbonation poses long-term durability concerns, especially concerning steel reinforcement corrosion and dimensional stability. The variability in findings regarding compressive and flexural strength post-carbonation indicates the need for standardized testing protocols and further investigation into long-term performance.

Several mitigation strategies have been identified to enhance CSA concrete's resistance to carbonation, including the incorporation of supplementary cementitious materials (SCMs), use of corrosion inhibitors, use of coatings, and optimization of water–cement ratios. The potential of early-age carbonation curing and the addition of layered double hydroxides (LDHs) to modify pore structure and immobilize carbonate ions present promising avenues for further research.

The geographical distribution of research indicates a global interest in CSA concrete, with significant contributions from the USA, China, and Europe. This international collaboration is crucial for advancing the understanding and application of CSA concrete in various environmental contexts.

For industry professionals and policymakers, the findings emphasize the importance of developing and implementing standards for CSA concrete use, promoting sustainable construction practices, and investing in further research to address the identified gaps. As the construction industry continues to seek low-carbon alternatives, CSA concrete represents a viable and promising option, provided its long-term performance and durability can be ensured through continued innovation and rigorous testing.

In conclusion, while CSA concrete offers substantial environmental benefits and promising performance characteristics, addressing its carbonation susceptibility is critical for its broader adoption. Future research should focus on long-term studies, innovative material formulations, and practical applications to fully realize the potential of CSA concrete in mitigating the environmental impact of construction activities.

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