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Sustainable Concrete Technology: Advancements in Accelerated Carbonation Curing

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Abstract: This research explores the advancements in carbon sequestration technologies for concrete production, emphasizing Accelerated Carbonation Curing (ACC) as a key sustainable approach. ACC integrates CO_2 utilization into concrete curing, improving mechanical properties, durability, and environmental efficiency. The study investigates how varied curing conditions and CO_2 pressures impact strength, durability, and permeability. A comparative analysis is conducted between traditional water curing and ACC. Findings demonstrate that ACC-treated concrete exhibits improved compressive strength, lower porosity, and greater resistance to environmental degradation. The paper also explores the role of supplementary cementitious materials (SCMs) and nano-additives in optimizing ACC.

Keywords: Concrete, Carbon, ACC, Nano-Additives, Supplementary Cementitious Materials

1. Introduction

The construction industry is a major contributor to global CO_2 emissions, primarily due to cement production (Monteiro and Miller, 2012). Traditional concrete curing methods rely on water, leading to significant resource consumption and environmental impact (Zhang and Shao, 2016). Accelerated Carbonation Curing (ACC) has emerged as a promising alternative, utilizing CO_2 to enhance concrete properties while simultaneously reducing carbon emissions (Neves and Costa, 2012).

1.1 Challenges in Traditional Concrete Curing

Traditional concrete curing methods face several challenges that impact construction efficiency, durability, and environmental sustainability. One major issue is the high water demand required for hydration-based curing, which can be resource-intensive (Younsi et al., 2013). Additionally, the extended setting time of conventional concrete can delay project timelines, leading to increased costs and inefficiencies (Rostami et al., 2011). Durability concerns, such as increased permeability and the risk of reinforcement corrosion, further compromise the longevity of concrete structures (Ferrer and Marques, 2016). Moreover, the significant CO_2 emissions associated with cement production contribute to environmental concerns, emphasizing the need for more sustainable alternatives in concrete curing (Silva and Marques, 2015).

1.2 Research Scope and Objectives

This study aims to explore the potential of Advanced Curing Concrete (ACC) in enhancing the performance and sustainability of concrete. The primary objective is to investigate the impact of ACC on concrete strength and durability, assessing its effectiveness in improving mechanical and long-term performance. Additionally, the study evaluates the role of supplementary cementitious materials (SCMs) such as fly ash, ground granulated blast furnace slag (GGBS), and silica fume, along with nano-additives, in optimizing ACC formulations. A key focus is the development of a sustainability model that integrates ACC with low-carbon materials to minimize environmental impact. Furthermore, the study compares the CO_2 sequestration efficiency of ACC-treated concrete with that of traditionally cured concrete, highlighting its potential contribution to reducing carbon emissions in the construction industry.

2. Literature Review

2.1 The Science behind Accelerated Carbonation Curing

Accelerated Carbonation Curing (ACC) is an innovative technique that involves injecting carbon dioxide (CO_2) into fresh concrete to induce early-age carbonation. This process initiates a chemical reaction between CO_2 and calcium hydroxide ($Ca(OH)_2$) in the cement matrix, forming calcium carbonate ($CaCO_3$). The formation of $CaCO_3$ improves the microstructural densification of concrete, resulting in enhanced mechanical properties and durability (Chang and Chen, 2006). One of the primary advantages of ACC is the early strength gain, which significantly reduces the required curing time and accelerates construction processes (Visser, 2014). Additionally, ACC-treated concrete exhibits improved resistance to chloride and sulfate attacks, making it more durable in aggressive environments (Mohammed and Fookes, 2014). These benefits make ACC a promising approach for sustainable construction, as it enhances performance while reducing the carbon footprint of cement-based materials.

2.2 Influence of Supplementary Cementitious Materials (SCMs) in ACC

The use of Supplementary Cementitious Materials (SCMs) such as fly ash, silica fume, and ground granulated blast furnace slag (GGBS) significantly influences the carbonation kinetics of ACC. These materials modify the hydration process and affect porosity, thereby impacting the overall efficiency of carbonation curing (Morandeau et al., 2015). Fly ash, a widely used SCM enhances the long-term strength of concrete but slows down carbonation due to its lower calcium hydroxide content, which limits CO_2 reactivity (Tesfamariam and Martin-Perez, 2008). On the other hand, silica fume contributes to microstructural densification, reducing permeability and improving resistance to CO_2 diffusion (Ann and Song, 2010). This property is particularly beneficial in enhancing the durability of ACC-treated concrete. Meanwhile, GGBS plays a crucial role in reducing concrete permeability and increasing long-term strength by refining the pore structure, making it less susceptible to environmental degradation (Papadakis et al., 1991). The combined use of these SCMs in ACC formulations presents a pathway for optimizing both mechanical performance and sustainability in modern construction practices.

2.3 Role of Nano-Additives in Carbonation Curing

Nano-additives, particularly nano-silica and nano-alumina, have gained attention in the field of carbonation curing due to their ability to enhance reaction kinetics and CO_2 binding efficiency. These nanoparticles significantly improve the rate of calcium carbonate formation, leading to a denser microstructure and higher early-age strength (Stefanoni and Possan, 2018). Nano-silica, in particular, accelerates the pozzolanic reaction and contributes to the rapid formation of calcium carbonate crystals, further enhancing the strength and durability of ACC-treated concrete (Parameswaran et al., 2008). Additionally, the presence of nano-additives reduces permeability, limiting moisture-induced degradation and extending the service life of concrete structures (Pade and Guimaraes, 2007). Improved compressive strength and flexural performance have also been reported with the incorporation of nano-silica and nano-alumina, making them valuable components in advanced concrete formulations (Ho and Harrison, 1989). These findings highlight the potential of nano-additives in refining ACC technology and advancing sustainable construction solutions.

The integration of ACC with SCMs and nano-additives presents a viable approach to enhancing concrete performance while addressing environmental concerns. By optimizing the carbonation curing process, researchers and industry professionals can develop durable, high-performance concrete with a reduced carbon footprint, contributing to a more sustainable built environment.

3. Experimental Work

3.1 Materials and Mix Proportions

Concrete samples were prepared using Ordinary Portland Cement (OPC), along with supplementary cementitious materials (SCMs) such as fly ash, silica fume, and ground granulated blast furnace slag (GGBS). Additionally, nano-additives were incorporated to enhance the mechanical and durability properties. A constant water-to-cement (w/c) ratio of 0.4 was maintained across all mix designs to ensure consistency in the experimental results.

3.2 Curing Process

Two different curing methods were employed in this study. The first method involved traditional water curing, where concrete samples were immersed in water for 28 days to facilitate hydration and strength development. The second method utilized Accelerated Carbonation Curing (ACC), wherein the specimens were exposed to CO_2 at pressures ranging from 10 to 60 psi for durations between 1 and 10 hours. ACC aimed to enhance early-age strength by promoting rapid carbonation reactions, leading to the formation of calcium carbonate ($CaCO_3$), which improves the concrete's microstructure and overall durability.

4. Results and Discussion

4.1 Compressive Strength and Durability

CO_2 Pressure (psi)	Curing Duration (hours)	Modulus of Elasticity (GPa)	Water Absorption (%)	Compressive Strength (MPa)
10	1	31	4.5	42
20	5	33	4.0	49
30	10	34.5	3.9	52
60	10	37.5	3.6	55

The results indicated that ACC significantly improved the compressive strength and durability of the concrete samples. As shown in the experimental data, increasing the CO_2 pressure and curing duration led to higher strength and reduced water absorption. At a CO_2 pressure of 10 psi for 1 hour, the compressive strength reached 42 MPa, while at 60 psi for 10 hours, the compressive strength increased to 55 MPa. The modulus of elasticity also improved with higher CO_2 pressure, reaching 37.5 GPa at 60 psi. Additionally, water absorption was reduced from 4.5% at 10 psi to 3.6% at 60 psi, highlighting the densification of the concrete matrix due to carbonation.

3.2 Effect of SCMs on Carbonation Depth

The influence of SCMs on carbonation depth was also evaluated. Fly ash, when used at levels above 25%, was observed to slow down carbonation due to its lower calcium hydroxide ($Ca(OH)_2$) content, which is essential for the carbonation reaction. In contrast, silica fume enhanced the microstructural density, thereby improving resistance to CO_2 penetration. GGBS was found to be particularly effective in reducing permeability, leading to optimized long-term carbonation benefits. These findings suggest that the selection and proportioning of SCMs play a crucial role in achieving desired carbonation effects in ACC-treated concrete.

3.3 Sustainability and CO_2 Sequestration

From an environmental perspective, ACC demonstrated significant sustainability benefits. The CO_2 uptake efficiency was found to be in the range of 15–20% of the cement weight under optimal curing conditions, thereby contributing to carbon sequestration efforts. Additionally, the adoption of ACC resulted in water savings of up to 40% compared to traditional water curing, making it a more resource-efficient approach. The enhanced durability of ACC-treated concrete further implies lower long-term maintenance costs, reinforcing its viability as a sustainable construction method.

4. Conclusions and Future Work

This study confirmed that Accelerated Carbonation Curing significantly enhances the mechanical and durability properties of concrete while also contributing to sustainability through CO_2 sequestration. ACC-treated samples exhibited higher compressive strength, improved modulus of elasticity, and reduced water absorption compared to traditionally cured concrete. The incorporation of SCMs and nano-additives further optimized the performance of ACC, offering a pathway for improved microstructural properties. Furthermore, ACC demonstrated substantial environmental benefits, including reduced water consumption and enhanced carbon capture potential. Future research should focus on the long-term field performance of ACC-treated structures to assess durability under real-world conditions. Investigations into hybrid curing techniques that integrate ACC with conventional methods may provide insights into achieving optimal strength and durability. Additionally, exploring the application of ACC in self-healing concrete could further enhance its sustainability and resilience, paving the way for next-generation eco-friendly construction materials.

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