A Critique Review on Effect of Carbonation of Concrete by Partially Replacement of Cement with Mineral Admixtures

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Abstract

Construction costs are rising in today's market, driven largely by high cement consumption. The production of cement is energy-intensive and contributes significantly to greenhouse gas emissions. As a result, researchers are exploring the potential to substitute waste materials in concrete as a way to reduce energy consumption and lessen environmental impacts. Replacing some traditional concrete components with waste by-products has shown promise in conserving energy and improving the sustainability of concrete production. In various studies, waste materials have been used to replace cement and sand, with materials such as Ground Granulated Blast-furnace Slag (GGBS), Fly Ash (FA), Rice Husk Ash (RHA), Silica Fume (SF), and Metakaolin (M) being explored as partial replacements for cement. This literature review examines the impact of these cementitious materials on two key properties of concrete: carbonation resistance and compressive strength. Carbonation is a chemical process where carbon dioxide from the atmosphere reacts with calcium hydroxide in concrete, forming calcium carbonate and lowering the concrete's pH. Over time, this process can lead to the corrosion of reinforcing steel, which compromises the structural integrity of concrete structures. Additionally, carbonation can reduce the concrete's overall strength and durability, negatively affecting the long-term performance of the structure.

Keywords: Ground Granulated Blast Furnace, Fly Ash, Rice husk ash, Metakaolin, Compressive strength, Carbonation Depth.

1. Introduction

Carbonation is a significant concern in reinforced concrete structures, primarily because it leads to corrosion of the reinforcing steel, which can result in structural degradation over time. Concrete's porous nature allows various substances to permeate through interconnected capillary pores. When carbon dioxide (CO_2) from the atmosphere enters the concrete and interacts with moisture, a chemical reaction occurs with calcium hydroxide ($Ca(OH)_2$) present in the concrete. This reaction forms calcium carbonate ($CaCO_3$) and reduces the alkalinity of the concrete's pore solution, which is essential for maintaining a protective environment around the embedded steel reinforcement. As the pH drops, the protective passive oxide layer around the reinforcing steel is compromised, making it more susceptible to corrosion.

This corrosion manifests as cracks, rust stains, and deterioration of the concrete cover, which undermines the structural integrity of the building. In reinforced concrete, the onset of corrosion in the reinforcement is a critical factor in determining the service life of the structure. Therefore, accurately predicting when the carbonation front will reach the level of the embedded rebar is crucial for assessing long-term durability.

The chemical process of carbonation involves the reaction of carbon dioxide (CO_2) with calcium hydroxide ($Ca(OH)_2$) in the concrete, producing calcium carbonate ($CaCO_3$) and water (H_2O)

$$Ca^{2+} + 2(OH^-) + CO_2 \longrightarrow CaCO_3 + H_2O$$

$$CO_2 + Ca(OH)_2 \longrightarrow CaCO_3 + H_2O$$

This reaction leads to a decrease in the pH of the concrete's pore solution, from around 13 to less than 9. As the pH drops, the passive oxide film that normally protects the steel reinforcement is broken down, allowing for uniform corrosion of the reinforcing bars. This is known as **carbonation-induced corrosion**.

Although carbonated concrete can retain its strength in some cases, it becomes more prone to rusting in the embedded steel, accelerating corrosion. This corrosion not only weakens the structural elements but also promotes crack formation, further reducing the durability of the concrete. Ultimately, carbonation-induced corrosion can significantly shorten the lifespan of reinforced concrete structures, leading to costly repairs and maintenance.

2. Literature Review

2.1 Utilization of Ground Granulated Blast Furnace (GGBS) in concrete

The studies reviewed highlight the impact of Ground Granulated Blast-Furnace Slag (GGBS) on the carbonation behaviour and compressive strength of concrete, especially in relation to different replacement levels of cement. Here's a summary of the key findings:

Yunusa Alhassan and Yunus Ballim (2017) investigated the carbonation behaviour of plain and blended cement concrete, focusing on early-age properties and carbonation in both inland and outdoor environments using Ground

Granulated Blast Furnace Slag (GGBS). Concrete cubes (100 mm) were cast with M30-grade concrete using a 1:1.7:2 mix ratio, a water-binder ratio (w/b) of 0.50, and binder content of 400 kg/m³. Cement was partially replaced with 50% GGBS. The compressive strength of the control concrete was measured at 3, 7, and 28 days, yielding 30 MPa, 41 MPa, and 62 MPa, respectively. For the 50% GGBS replacement mix, compressive strength decreased by 37%, 39% and 19% respectively. Carbonation tests were conducted in both indoor conditions (32% relative humidity, 24°C) and outdoor conditions (49% relative humidity, 19°C). In indoor conditions, carbonation depths for the control mix were 4 mm, 3 mm and 2 mm at 3, 7 and 28 days, respectively. With 50% GGBS replacement, carbonation depths increased to 9 mm, 7.5 mm and 5.5 mm. In outdoor conditions, carbonation depths for the control mix were 5 mm, 3.8 mm and 2.5 mm, and for the 50% GGBS replacement, they increased to 10 mm, 7 mm and 5 mm at the same respective ages.

Adam et al., (2007) investigated the compressive strength and carbonation behaviour of alkali-activated slag (AAS) blended concrete, with cement replacement levels of 30%, 50% and 70% using GGBS. The concrete was prepared with a water-binder ratio (w/b) of 0.5 and an M 30-grade mix ratio of 1:1.8:2.4. Specimens (100 mm x 200 mm high cylinders) were cast and carbonation depth was evaluated at weekly intervals by applying phenolphthalein indicator on split specimens. The compressive strength of the control mix at 28 days was 50 MPa. With GGBS replacements of 30%, 50% and 70%, the strength decreased by 4%, 4% and 30% respectively. The study found that up to 70% GGBS replacement maintained acceptable strength and durability. However, carbonation depth increased as the level of GGBS replacement increased. Carbonation depths were observed to be 6 mm for the control mix and increased to 8 mm, 12 mm and 15 mm for 30%, 50% and 70% GGBS replacements, respectively.

Belie et al., (2013) examined the impact of cement replacement levels on the carbonation coefficient of concrete, conducting accelerated carbonation tests on specimens with varying blast furnace slag (BFS) content: 50%, 70% and 85% slag-to-binder. M30-grade concrete was used with a mix ratio of 1:2.2:3 and a water-binder ratio (w/b) of 0.5, casting 100 mm x 100 mm x 100 mm cubes. Carbonation depth was determined by applying phenolphthalein to freshly cut surfaces, where carbonated areas remained colourless and non-carbonated areas turned purple. After a 4-week curing period under conditions of 95% relative humidity and 20°C, no carbonation was observed for the control concrete. For the concrete with 85% slag replacement, the carbonation depth reached 8.6 mm, indicating that higher levels of BFS replacement accelerated the carbonation process.

Gashaw Assefa Bezabih et al., (2021) conducted an experimental study to examine the effects of partial cement replacement with Ground Granulated Blast-Furnace Slag (GGBS) on the compressive strength and carbonation behaviour of concrete. The study involved replacing 30%, 50% and 70% of cement with GGBS in M30-grade concrete, using a mix ratio of 1:1.7:2.4 and a water-binder ratio (w/b) of 0.47. Concrete cubes of 100 mm were cast for testing. The compressive strength of the control concrete at 28 days was observed to be 32 MPa. For mixes with 30% and 50% GGBS replacement, the strength increased by 10% and 13% respectively. However, with 70% GGBS replacement, the compressive strength decreased by 37%. Carbonation depth for the control concrete was 3 mm and it increased to 6 mm, 7.5 mm and 14 mm for 30%, 50% and 70% GGBS replacements respectively. These findings suggest that while a 30% to 50% replacement of cement with GGBS can improve the compressive strength, a 70% replacement leads to a significant decline in both strength and carbonation resistance.

Xiantang Zhang (2013) also studied the effect of partial cement replacement with slag on concrete carbonation. In this study, slag was replaced in multiples of 15%, up to 60%, in M30-grade concrete, with mix ratios of 1:1.3:1.9 and water-binder ratios (w/b) of 0.30 and 0.35. Concrete specimens with dimensions of 100 mm x 100 mm x 300 mm were cast and tested for carbonation depth after 28 days of curing. For the mix with a w/b ratio of 0.30, carbonation depth was 2.2 mm for 15% slag replacement, and it increased to 2.7 mm, 3.3 mm and 4 mm for 30%, 45% and 60% slag replacements, respectively. On the other hand, for a w/b ratio of 0.35, the carbonation depth was 2.8 mm for 15% slag replacement and decreased by 1.7 mm, 1.3 mm, and 2.2 mm for 30%, 45%, and 60% slag replacements. These results indicate that increasing the slag replacement level tends to increase the carbonation depth, whereas higher water content in the mix (higher w/b ratio) tends to reduce the carbonation depth.

Observations and Conclusion:

- **Compressive Strength**: Moderate levels of GGBS replacement (30%-50%) generally enhance the compressive strength, but excessive replacement (e.g., 70%) significantly reduces strength.
- **Carbonation Resistance**: As GGBS content increases, the carbonation depth tends to increase, with higher slag content accelerating carbonation. However, this effect is moderated by factors like water-binder ratio. Higher water content (increased w/b ratio) can reduce carbonation depth, even with higher slag content.
- **Durability Implications**: While GGBS can improve the sustainability and strength of concrete at moderate replacement levels, high GGBS replacement reduces both strength and carbonation resistance, which may compromise long-term durability.

These findings underline the importance of optimizing the proportion of GGBS replacement in concrete mixes to balance both strength and durability, especially when considering the long-term performance and environmental impact of concrete structures.

2.2 Utilization of Fly Ash (FA) in concrete

The studies highlight the influence of partial cement replacement with fly ash and other supplementary materials, such as Alccofine, marble dust, and recycled concrete aggregates on the carbonation behaviour and mechanical properties of concrete.

Pravalika and Venkat Rao (2018) conducted a study to investigate the effects of partial cement replacement with fly ash on the compressive strength and carbonation behaviour of concrete. M30-grade concrete was prepared using a mix ratio of 1:2:3 and a water-binder ratio of 0.5 with 150 mm cubes cast for testing. The cement was replaced with fly ash in increments of 5%. The cubes were then subjected to accelerated carbonation in a chamber and carbonation depth was measured by spraying phenolphthalein solution on the fractured surfaces, where the carbonated zones appeared colourless. The compressive strength of the control mix at 28 days was 34 MPa. For the fly ash replacement mixes, the strength increased by 6%, 12%, 25%, 13% and 8% for 5%, 10%, 15%, 20% and 25% fly ash replacements, respectively. However, the strength decreased by 4% for the 30% fly ash replacement. Regarding carbonation depth, the control mix showed a carbonation depth of 8 mm after 28 days. As the fly ash replacement level increased, the carbonation depth also increased, reaching the maximum of 24 mm at 15% fly ash replacement. The carbonation depths for the various replacement levels were as follows: 12 mm for 5%, 18 mm for 10%, 24 mm for 15%, 21 mm for 20%, 16 mm for 25%, and 11 mm for 30% replacement. The maximum carbonation depth was observed at 15% fly ash replacement.

Cengiz Duran Atis (2002) conducted an experimental study to assess the carbonation behaviour of concrete in a controlled environment using an accelerated carbonation test. The study involved concrete mixtures with 0%, 50% and 70% replacement of normal Portland cement with fly ash. The water-cementitious material ratios ranged from 0.28 to 0.55, and the concrete was mixed to M40 grade with a mix ratio of 1:1.5:3. Concrete cubes (100 mm) were cast, both compressive strength and carbonation depth were monitored over a 28-day curing period. The compressive strength of the control concrete mix at 28 days was 48 MPa. For the 50% fly ash replacement, the compressive strength increased by 38%, while for the 70% fly ash replacement, it decreased by 30%. Carbonation testing was conducted under two different relative humidity conditions: 65% at 20°C and 100% at 20°C. The carbonation depth for the control concrete was 6 mm after 28 days. With 50% fly ash replacement, the carbonation depth increased to 11.3 mm, and for 70% fly ash replacement, it increased to 6.3 mm under the same conditions. Under 100% relative humidity, the carbonation depth for the control mix was 4.5 mm, which increased to 7 mm and 3 mm for the 50% and 70% fly ash replacements respectively. These results indicate that while 50% fly ash replacement enhances strength, it also increases carbonation depth, whereas 70% replacement leads to both decreased strength and a varying impact on carbonation depth.

Younsi et al. (2011) investigated the durability of fly ash concrete exposed to carbonation, aiming to reduce cement content and mitigate CO_2 emissions associated with Portland cement clinker production. The study involved concrete mixtures with 0%, 30% and 50% cement replacement by fly ash. M30 grade concrete was used with a mix ratio of 1:2.8:3.6 and a water-binder ratio (w/b) of 0.67. Concrete cylinders measuring 100 mm x 220 mm were cast and subjected to both air and water curing for 7 and 28 days. The compressive strength of the control concrete was observed to be 26 MPa at 7 days and 35 MPa at 28 days. For the 30% fly ash replacement, the compressive strength remained similar to the control mix, while for the 50% replacement, it decreased by 23% at 7 days. At 28 days, the compressive strength for 30% and 50% replacements decreased by 8% and 12%, respectively. In terms of carbonation, the depth for the control mix was 2.5 mm after 28 days. The carbonation depth increased to 4 mm and 3.7 mm for the 30% and 50% fly ash replacements respectively. For specimens subjected to air curing at 20 ± 2°C and 65 ± 5% relative humidity, the carbonation depth at 28 days was 6 mm, which increased to 7.5 mm with the 30% and 50% fly ash replacements. Notably, carbonation depths were found to be 20-50% lower for specimens subjected to water curing compared to those exposed to air curing. These results highlight the impact of fly ash on both the compressive strength and carbonation resistance of concrete with higher fly ash replacement levels leading to increased carbonation depth.

Hussain et al. (2017) conducted a study on the accelerated carbonation of concrete with partial replacement of cement by fly ash, focusing on various mechanical properties such as compressive strength, flexural strength and carbonation depth. The concrete mixtures included 0%, 30%, 40% and 50% replacement of cement with fly ash. M30 grade concrete was prepared with a mix ratio of 1:1.2:2.4 and water-binder ratios (w/b) of 0.35, 0.50, and 0.65. Concrete specimens in the form of 150 mm cubes, 100 mm × 100 mm × 50 mm prisms and 150 mm diameter × 300 mm height cylinders were cast to test for compressive strength, flexural strength, and carbonation depth respectively. The compressive strength of the control mix after 28 days was 33 MPa. The strength increased by 6% for the 30% fly ash replacement, but it decreased by 24% and 39% for the 40% and 50% replacements, respectively. In terms of carbonation, the control concrete exhibited a carbonation depth of 3 mm after 28 days, which increased to 8 mm, 11 mm and 20 mm for the 30%, 40%, and 50% fly ash replacements respectively. The study also found that the mechanical properties of the carbonated concrete improved as the exposure duration to carbon dioxide increased. This suggests that while increasing the fly ash replacement levels led to reduced compressive strength and greater carbonation depths, prolonged carbonation exposure may contribute to enhanced mechanical properties in the carbonated zone.

Vedran Carevic (2019) investigated the carbonation behaviour of concrete with partial cement replacement by fly ash and recycled concrete aggregate (RCA). The study focused on two mixtures: one with 50% fly ash replacement and the other with 100% recycled aggregate. M30 grade concrete was used with a mix ratio of 1:2.8:3.4. The water-binder ratio was 0.6 for the control concrete and 0.48 for the fly ash mixture. Concrete specimens were cast as 100 mm cubes for compressive strength tests and 100 mm × 100 mm × 360 mm prisms for carbonation depth analysis. The compressive strength of the control concrete after 28 days was 42.7 MPa. For the recycled aggregate concrete, the strength decreased by 2.5%, while the concrete with 50% fly ash replacement experienced a more significant reduction, with strength dropping by 24.5%. To assess carbonation, the concrete specimens were subjected to four different CO_2 concentrations (1%, 2%, 4% and 16%) in an accelerated carbonation chamber. The carbonation depth after 28 days at a 1% CO_2 concentration was 1.6 mm for the control mix, 2.7 mm for the recycled aggregate concrete, and 4 mm for the fly ash mix. As the CO_2 concentration increased to 2%, the carbonation depths grew to 1.8 mm, 3.3 mm and 4 mm for the control, recycled aggregate, and fly ash mixtures, respectively. Further increases in CO_2 concentration led to carbonation depths of 2.8 mm, 3.9 mm and 6 mm for 4% CO_2, and 3.4 mm, 6 mm, and 9.6 mm for 16% CO_2 concentration. The results indicated that both recycled aggregate and fly ash concrete exhibited greater carbonation depths compared to the control concrete. This suggests that while incorporating fly ash or recycled aggregate into concrete may reduce strength, it can also influence the carbonation behaviour, making the material more susceptible to carbonation under high CO_2 concentrations.

Narasimha and Kavyateja (2020) conducted an experimental study to investigate the effects of partial cement replacement with fly ash and low-heat cement (Alccofine) on the carbonation depth of concrete. The study involved a constant 30% fly ash replacement, while the Alccofine content varied from 0% to 16%, in increments of 4%. M30-grade concrete was prepared with a mix ratio of 1:1.1:1.5 and a water-binder ratio (w/b) of 0.3, along with 1.5% superplasticizer. Concrete cubes with a dimension of 100 mm were cast and cured for 28 days to assess the carbonation depth. For the control mix, which included 30% fly ash and 0% Alccofine, the carbonation depth was observed to be 17 mm after 28 days. When Alccofine was added at 4%, the carbonation depth decreased to 11 mm and further reductions were observed as the Alccofine content increased. The carbonation depth decreased to 8.16 mm, 5.1 mm and 4.1 mm for 8%, 12% and 16% Alccofine replacement respectively. These results indicate that as the percentage of Alccofine increased, the carbonation depth decreased, suggesting that low-heat cement (Alccofine) has a positive effect on reducing the carbonation susceptibility of fly ash-based concrete.

Jitu Kujur et al. (2017) investigated the carbonation behaviour of Portland pozzolana cement concrete with 25% fly ash and varying amounts of marble dust as a supplementary material. Marble dust was incorporated in multiples of 5%, up to a maximum of 20%. The study focused on the effects of marble dust addition on both compressive strength and carbonation depth of the concrete. The concrete was mixed with a water-binder ratio (w/b) of 0.5 for compressive strength testing and 0.7 for carbonation testing. The mix ratios were 1:1.4:3.2 for compressive strength and 1:2.4:4.5 for carbonation. For compressive strength, 150 mm cubes were cast and cured for 28 days. The control mix (w/b = 0.5) had a compressive strength of 24 MPa and the strength increased by 4%, 20%, and 8% with 5%, 10%, and 15% marble dust replacement respectively. However, it decreased by 4% when 20% marble dust was added. For carbonation testing, carbonation depth was measured after 70 days of exposure to accelerated carbonation conditions (w/b = 0.7). The carbonation depth for the control mix (0% marble dust) was found to be 7 mm. When 5% marble dust was added, the carbonation depth decreased to 6.3 mm. However, further increases in marble dust content (10%, 15%, and 20%) resulted in a slight increase in carbonation depth with values of 7.18 mm, 7.1 mm and 7 mm respectively. These results suggest that while a 5% addition of marble dust reduced carbonation depth, higher replacement levels of marble dust did not significantly affect carbonation and even caused a slight increase in depth.

Observations and Conclusion:

The studies confirm that partial cement replacement with fly ash generally improves strength at moderate levels (up to 30%) but increases carbonation depth, especially at higher replacement levels. The use of supplementary materials like Alccofine, marble dust, and recycled aggregates can influence carbonation behavior, with Alccofine showing the most promise in reducing carbonation depth. Proper curing conditions also play a crucial role in reducing carbonation, particularly when using fly ash as a partial cement replacement.

2.3 Utilization of Fly Ash (FA) and Ground Granulated blast furnace (GGBS) in concrete

The incorporation of supplementary cementitious materials (SCMs) like Fly Ash (FA) and Ground Granulated Blast Furnace Slag (GGBS) in concrete offers both economic and environmental benefits. These materials can partially replace Ordinary Portland Cement (OPC) in concrete, leading to a reduction in CO_2 emissions associated with cement production. Several studies have investigated the impact of these replacements on the mechanical properties and durability of concrete, particularly in terms of compressive strength and carbonation resistance.

Bhunia et al. (2013) investigated the effects of carbonation on the mechanical properties of plain concrete. M30-grade concrete was prepared using a mix ratio of 1:1.8:3.3 and a water-binder ratio (w/b) of 0.5. Concrete cubes of 100 mm size were cast and tested for compressive strength at 7 and 28 days of curing. The carbonation depth was also measured at regular intervals (2, 4 and 6 months). To determine the carbonated zone, phenolphthalein solution was sprayed on the fractured surfaces of the cubes. The results showed that the compressive strength of the control concrete at 7 days was 33.96 MPa, which increased to 35 MPa after 28 days. In terms of carbonation depth, the concrete exhibited a carbonation depth of 3 mm at 2 months, which increased to 5 mm at 4 months, and reached 14 mm after 6 months. These findings highlight the progressive increase in carbonation depth over time, indicating that plain concrete becomes more susceptible to carbonation with its age.

Sakr and Bassuoni (2020) conducted an experimental study to evaluate the effects of partial cement replacement with Ground Granulated Blast Furnace Slag (GGBS) and Fly Ash on the compressive strength and carbonation of concrete. The study used M30-grade concrete with a mix ratio of 1:1.55:3 and a water-binder ratio (w/b) of 0.5. GGBS was used at replacement levels of 30% and 60%, while Fly Ash was used at 20% and 40% replacements. Concrete cubes of 100 mm size were cast and tested for compressive strength and carbonation depth. The results showed that the compressive strength of the control mix was 38 MPa at 28 days. For Fly Ash replacement, the compressive strength increased by 3% for 20% replacement but decreased by 5% for 40% replacement. For GGBS replacement, the compressive strength remained the same as the control mix for 30% replacement but decreased by 13% for 60% replacement. Regarding carbonation depth, the control concrete exhibited a carbonation depth of 3 mm after 28 days. The carbonation depth increased to 3.5 mm and 4 mm for 20% and 40% Fly Ash replacements, respectively. For GGBS replacement, the carbonation depth increased to 3.7 mm for 30% replacement and 8 mm for 60% replacement. These findings suggest that while Fly Ash and GGBS replacements had a moderate effect on compressive strength, both contributed to an increase in carbonation depth with higher carbonation observed for higher replacement levels, particularly for GGBS.

Fly Ash and GGBS can be effectively utilized as partial replacements for Ordinary Portland Cement to enhance sustainability in concrete production. However, their impact on carbonation resistance should be carefully considered, particularly when higher replacement levels are used.

2.4 Utilization of Rice husk ash (RHA) in concrete

Rice Husk Ash (RHA) is an industrial by-product derived from the combustion of rice husks, often used as a supplementary cementitious material (SCM) in concrete. Its utilization not only contributes to sustainability by reducing waste but also has potential benefits for concrete properties, particularly in terms of compressive strength and carbonation resistance. Several studies have investigated the effects of RHA on these properties, demonstrating both positive and negative impacts, depending on the level of replacement.

Nisar and Bhat (2020) conducted an experimental study to assess the impact of Rice Husk Ash (RHA) as a partial cement replacement in concrete, with replacement levels ranging from 5% to 20%. In this study, M30 grade concrete used with a mix ratio of 1:2.2:4.3 and a water-binder ratio of 0.45. Concrete cubes of 100 mm size were cast for compressive strength testing and prisms measuring 100 mm x 100 mm x 500 mm were used to determine carbonation depth. The results showed that the compressive strength of the control concrete was 29.8 MPa at 28 days. With RHA replacement, the compressive strength increased by 2.8% for 5% replacement, 4.3% for 10%, 7% for 15% and 0.5% for 20% replacement. Regarding carbonation depth, the control concrete exhibited a depth of 1.10 mm which increased to 1.7 mm, 2.0 mm, 2.3 mm and 2.4 mm for 5%, 10%, 15% and 20% RHA replacement respectively. These findings suggest that while RHA improves compressive strength upto certain replacement levels, it also leads to increased carbonation depth, particularly at higher replacement levels.

Chatveera and Lertwattanaruk (2010) investigated the carbonation depth of concrete incorporating ground black rice husk ash (RHA) as a partial replacement for cement. The study used two replacement levels: 20% and 40% with M30 grade concrete prepared using a mix ratio of 1:3:3 and a water-binder ratio of 0.6. Concrete cubes of 100 mm size were cast and cured for 28 days. The compressive strength of the control mix was 27.5 MPa at 28 days which increased by 6.5% for the 20% RHA replacement but decreased by 2% for the 40% replacement. To measure carbonation depth, phenolphthalein was applied to freshly broken cubes. The carbonation depth for the control mix was 3.5 mm, which increased to 3.9 mm for the 20% RHA replacement and 5.3 mm for the 40% replacement. The results indicated that carbonation depth increased with higher levels of RHA replacement, highlighting the influence of RHA content on both compressive strength and carbonation susceptibility in concrete.

Observations and Conclusion:

Rice Husk Ash (RHA) is a viable supplementary cementitious material for improving the compressive strength of concrete, especially at moderate replacement levels (5% to 15%). However, higher replacement levels (20% and above) may reduce the strength benefits and increase the carbonation depth, which could affect the durability of the concrete. As such, while RHA can be an environmentally friendly and cost-effective material in concrete, its impact on carbonation resistance should be considered when designing for long-term durability in aggressive environments.

2.5 Utilization of Rice Husk Ash (RHA) and Metakaolin (M) in concrete

The studies focused on the utilization of Rice Husk Ash (RHA) and Metakaolin (M) in concrete, present valuable insights into the effects of supplementary cementitious materials and recycled aggregates on the carbonation and mechanical properties of concrete.

Navdeep Singh (2016) studied the carbonation behaviour of self-compacting concrete incorporating coarse recycled concrete aggregates (RCA). The concrete mixes were designed by replacing natural coarse aggregates with recycled aggregates and fly ash and metakaolin were used as partial replacements for cement. The control mix included 42% fly ash as a cement replacement, while 10% metakaolin replaced a portion of the cement in the mix. The concrete used was M30 grade, with a mix ratio of 1:1.3:1.05 and a constant water-binder (w/b) ratio of 0.45. Accelerated carbonation tests were performed on concrete prisms (100 mm × 100 mm × 500 mm) with a 4-week exposure period. The compressive strength of the control mix was 40 MPa which increased by 7.5% with the addition of 10% metakaolin and 25% recycled aggregates. The carbonation depth of the control mix was 10 mm, which increased to 15 mm when 100% recycled aggregates replaced the natural aggregates.

Muduli and Mukharjee (2019) investigated the effects of different metakaolin replacement levels on the mechanical and durability properties of recycled aggregate concrete (RAC). In this study, natural coarse aggregates replaced with 50% and 100% recycled coarse aggregates and varied the metakaolin content as a partial cement replacement at 0%, 5%, 10%, 15% and 20%. The concrete mix was of M30 grade, with a mix ratio of 1:1.6:2.9 and a water-binder (w/b) ratio of 0.43. Concrete cubes (150 mm) were cast and cured for 28 days. The results showed that the compressive strength of the control mix (without metakaolin) was 40.5

MPa. For mixes with 15% metakaolin, the compressive strength decreased by 1.25% and 6.2% when 50% and 100% of the natural aggregates were replaced with recycled aggregates, respectively. In terms of carbonation depth, the control mix had a carbonation depth of 4 mm which increased to 4.7 mm and 5.2 mm when 50% and 100% recycled aggregates were used respectively, with no metakaolin replacement. The study observed that mixes with higher carbonation depths tended to exhibit lower compressive strength, highlighting the negative impact of carbonation on the durability and mechanical properties of RAC.

Observations and Conclusions:

- **Metakaolin as a Supplementary Cementitious Material (SCM)**: In both studies, the incorporation of metakaolin positively influenced the mechanical properties (compressive strength) of concrete to some extent. In Singh's study, 10% metakaolin improved compressive strength by 7.5%, while in Muduli and Mukharjee's study, higher doses of metakaolin (up to 20%) led to a slight decrease in strength when 100% recycled aggregates were used.
- **Recycled Aggregate and Carbonation Depth**: Replacing natural aggregates with recycled concrete aggregates (RCA) increased the carbonation depth in both studies. This is likely because recycled aggregates can have higher porosity and greater permeability, which allows carbon dioxide to penetrate deeper into the concrete matrix.
- **Effect of Carbonation on Durability**: Both studies showed a trend where increased carbonation depth correlated with decreased compressive strength, highlighting the importance of controlling carbonation for ensuring the durability of concrete. This is particularly critical for self-compacting concrete and recycled aggregate concrete, which may have more porous and less dense microstructures compared to conventional concrete.

2.6 Utilization of Fly ash (FA) and Silica Fume (SF) in Concrete

The studies highlight the impact of fly ash (FA) and silica fume (SF) on the carbonation behaviour and mechanical properties of concrete. These materials, used as partial replacements for cement, can improve the sustainability and durability of concrete but also come with trade-offs in terms of strength and carbonation resistance.

Khalil and Anwar (2014) studied the carbonation behaviour of concrete incorporating fly ash and silica fume as partial cement replacements. The concrete mix used was M40 grade, with a mix ratio of 1:1.6:2.4 and a water-binder (w/b) ratio of 0.4. Concrete cubes (150 mm) were cast and cured for 28 days. In the study, fly ash was used as a constant 25% replacement for cement, while silica fume was used at two levels, 5% and 10%. The results showed that the compressive strength of the control mix (without supplementary cementitious materials) was 63 MPa. The compressive strength decreased by 5% when 25% fly ash was used, and by 10% when 10% silica fume was incorporated. In terms of carbonation depth, the control mix had a depth of 4 mm, which increased to 7.3 mm and 7.4 mm for the mix with 25% fly ash. For the silica fume mixes, the carbonation depth was 4.2 mm and 4.6 mm for 5% and 10% silica fume replacements, respectively.

Jiho Moon (2020) examined the effects of partial cement replacement with fly ash, silica fume, and nano-silica on the carbonation depth and compressive strength of concrete. The concrete used was M40 grade, with a mix ratio of 1:1.6:2 and a water-binder (w/b) ratio of 0.36, with the addition of a water-reducing chemical admixture. Concrete cylinders (100 mm × 200 mm) were cast and cured for 28 days, and carbonation tests were performed on prisms (100 mm × 100 mm × 400 mm). The compressive strength of the control concrete was 48 MPa. The strength increased by 2% with 2% nano-silica, 10% with 15% fly ash, and 12% with 3.5% silica fume. For carbonation depth, the control mix had a depth of 4 mm, which increased to 6 mm when 15% fly ash was used. However, the carbonation depth decreased by 1.5 mm and 1.4 mm when 3.5% silica fume and 2% nano-silica were used respectively. These results indicate that silica fume and nano-silica help reduce the carbonation depth, improving the durability of the concrete, while fly ash increases the carbonation depth compared to the control.

Observations and Conclusion:

- **Fly Ash**: While fly ash provides sustainability benefits by utilizing industrial waste, it tends to increase carbonation depth, which can be a concern for the durability of concrete exposed to carbon dioxide.
- **Silica Fume**: Silica fume appears to improve both compressive strength and carbonation resistance to some extent, particularly in lower dosages (5-10%). It has a positive impact on the durability of concrete and can be beneficial for applications where reduced permeability and improved resistance to carbonation are crucial.
- **Nano-Silica**: Nano-silica is the most effective of the three materials in reducing carbonation depth and enhancing compressive strength. This makes it an excellent choice for improving the long-term durability of concrete, especially in aggressive environments.
- **Durability vs. Strength**: The studies indicate a clear relationship between carbonation depth and compressive strength**.** While fly ash increases carbonation depth, silica fume and nano-silica help mitigate this effect, thereby improving the overall durability of concrete.

In conclusion, while fly ash can provide sustainability advantages, its effect on carbonation depth must be balanced with the concrete's required durability. Silica fume and nano-silica offer improved resistance to carbonation, making them better choices when durability against carbonation is a key design criterion.

2.7 Utilization of Sugarcane Bagasse (SB) in Concrete

The incorporation of Sugarcane Bagasse Ash (SCBA) in concrete has been studied to assess its effects on carbonation behaviour, compressive strength and durability.

Ribeiro (2020) conducted an experimental study to investigate the carbonation behaviour of concrete with partial replacement of cement by sugarcane bagasse ash (SCBA) at replacement levels of 5%, 10%, and 15%. The concrete used was M40 grade, with a mix ratio of 1:1.6:2.2 and a water-binder ratio of 0.5. Concrete cylinders (100 mm × 200 mm) were cast and cured for 3 weeks. After curing, the carbonated cubes were broken, and the fractured surfaces were cleaned. To assess carbonation, phenolphthalein was sprayed on the freshly broken concrete, where the non-carbonated areas turned purple-red and the carbonated areas remained colourless. The carbonation depth for the control mix was 5 mm, which increased to 7 mm, 7.5 mm and 9 mm for concrete with 5%, 10% and 15% SCBA replacement respectively. The results showed that concrete containing bagasse ash exhibited a higher carbonation rate compared to the control mix, indicating that the inclusion of SCBA accelerates the carbonation process.

Chandradeo (2021) studied the effect of sugarcane bagasse ash (SCBA) as a partial replacement for cement on the carbonation depth of concrete. In this study, SCBA was used at replacement levels of 5%, 10%, 15% and 20%. The concrete used was M30 grade, with a mix ratio of 1:3.2:3 and a water-binder ratio (w/b) of 0.57. Concrete cubes (150 mm) and prisms (150 mm × 150 mm × 600 mm) were cast and cured for 28 days. The compressive strength of the control concrete was 38 MPa which decreased by 3%, 10%, 18% and 39% with 5%, 10%, 15% and 20% SCBA replacement, respectively. Similarly, the flexural strength of the control concrete was 4.7 MPa and it decreased by 2%, 8%, 15% and 23% for the respective SCBA replacement levels. In terms of carbonation depth, the control concrete exhibited a depth of 1 mm after 180 days of exposure, which increased to 1.2 mm, 1.8 mm, 2 mm and 4 mm for the 5%, 10%, 15% and 20% SCBA replacement levels. After 360 days, the carbonation depth of the control concrete increased to 1.8 mm, while the depth for 5%, 10%, 15% and 20% SCBA replacement increased to 2 mm, 2.8 mm, 3 mm and 7 mm respectively. The results showed that as the percentage of SCBA increased, the carbonation rate also increased, indicating that higher SCBA content accelerates the carbonation process in concrete.

Observations and Conclusion:

- **Carbonation Depth**: Studies show that sugarcane bagasse ash increases carbonation depth in concrete. This could be problematic for structures exposed to carbon dioxide, as increased carbonation depth may reduce the concrete's durability, leading to potential degradation over time.
- **Mechanical Properties**: Replacing cement with SCBA reduces the compressive and flexural strength of concrete, with a more significant reduction at higher replacement levels. This suggests that while SCBA may be a cost-effective and sustainable option, it should be used with caution, particularly in structural applications requiring high strength.
- **Sustainability Considerations**: While the use of SCBA offers a way to recycle agricultural waste and reduce the environmental impact of cement production, its effects on concrete durability—especially in terms of carbonation resistance—must be carefully considered. SCBA may be more suitable for non-structural applications or where carbonation resistance is less critical.
- **Durability**: The increased carbonation rate with higher SCBA content indicates that while SCBA can be a sustainable alternative for cement replacement, it may compromise the long-term durability of concrete, particularly in environments with high CO_2 exposure.

In conclusion, sugarcane bagasse ash can be used as a partial replacement for cement in concrete, but its incorporation should be carefully controlled, especially in applications where durability and carbonation resistance are critical. The increasing carbonation depth with higher SCBA content suggests that alternative materials or supplementary treatments may be needed to enhance the concrete's long-term performance in such environments.

2.8 Combination of supplementary cementitious materials in Concrete

Martin et al. (2017) conducted an experimental study on metakaolin-based concrete exposed to carbonation, incorporating various supplementary cementitious materials (SCMs) such as fly ash, blast furnace slag, and limestone filler. The study involved several concrete mixes with different combinations of these additives, including 16% limestone cement, 15% fly ash, 62% ground granulated blast-furnace slag (GGBS) and metakaolin replacements ranging from 15% to 25%. The M30 grade concrete had a mix ratio of 1:2.6:4.1 with a water-binder ratio of 0.6 and 0.53. Concrete cubes (100 mm) were cast and cured for 28 days. The compressive strength of the control concrete was 49 MPa and showed variations with different mixes. Some blends showed an increase in compressive strength by 9%, while others showed reductions of up to 3.2%. Carbonation depth was measured and ranged from 9.5 mm for the control concrete, increasing to as much as 21 mm for some of the blended mixes. The study found that the replacement of OPC with blended cements increased the carbonation depth, with mixtures containing a higher percentage of GGBS and fly ash exhibiting a greater carbonation depth.

Sun et al. (2007) examined the carbonation and compressive strength of concrete made with various cement blends, including ordinary Portland cement (OPC) mixed with 30% pulverized fuel ash (PFA), 50% ground granulated blast-furnace slag (GGBS), 10% metakaolin, and 10% micro-silica. The study used M40 grade concrete with a mix ratio of 1:2.1:3.2 and a constant water-binder ratio (w/b) of 0.5. Concrete cubes (100 mm) were cast and cured for 28 days to determine compressive strength, while carbonation depth was measured on prisms (250 mm x 250 mm x 100 mm) exposed for 70 days. The control concrete had a compressive strength of 49.4 MPa, which decreased by up to 20% with 30% PFA and 50% GGBS replacement, while mixes with 10% metakaolin and 10% micro-silica showed increased strength by 17% and 7% respectively. The carbonation depth of the control concrete was 10 mm and it increased to 21 mm, 18 mm, 16 mm and 14 mm for the PFA mixes. The metakaolin mix exhibited the highest compressive strength, while the PFA mix showed the lowest, primarily due to the slower pozzolanic reaction of PFA. The study demonstrated that while metakaolin enhanced strength, the inclusion of PFA and GGBS contributed to increased carbonation depth.

Eldin et al. (2022) investigated the carbonation rate of concrete incorporating Rice Husk Ash (RHA) as a partial replacement for cement at levels of 5%, 10%, and 15%. The study also examined the effect of two concentrations of soap solution (1% and 2%) on the carbonation behaviour. The concrete used was M30 grade, with a mix ratio of 1:2.3:3.8 and a water-binder ratio (w/b) of 0.5. Concrete cubes (150 mm) were cast and cured for 28 days and carbonation depth was measured over a period of 70 days. The control concrete, with 1% soap solution, had a compressive strength of 28 MPa at 28 days, which decreased by 5%, 7%, and 21% with 5%, 10%, and 15% RHA replacement, respectively. When exposed to 2% soap solution, the compressive strength of the control concrete decreased to 25 MPa, with reductions of 4%, 10%, and 16% for 5%, 10%, and 15% RHA replacements. Regarding carbonation depth, the control concrete with 1% soap solution exhibited a depth of 11 mm, which decreased slightly to 9.8 mm and 9.6 mm for the 5% and 10% RHA mixes, but increased to 12.6 mm for the 15% RHA replacement. With the 2% soap solution, the carbonation depth of the control concrete was also 11 mm, but it decreased to 6.2 mm, 5.18 mm, and 4.7 mm for 5%, 10%, and 15% RHA, respectively, before increasing to 13.2 mm for the 15% RHA replacement. The study showed that while 1% soap solution generally increased the carbonation depth, higher RHA content accelerated the carbonation process.

These studies underscore the importance of SCMs in both improving and altering the durability characteristics of concrete. While certain replacements, such as metakaolin and micro-silica, improved compressive strength, others like RHA and PFA accelerated carbonation, which may affect the long-term durability of concrete, especially in environments prone to carbonation-induced corrosion.

Table 1. Critical Review of Carbonation of Concrete

Author name	Grade of concrete with mix proportion	Materials used and %replacement of cement	Parameters	Conclusion
Yunusa Alhassan and Yunus Ballim (2017)	M 30, w/b=0.40,0.50, 0.60, 0.75.	GGBS replacement of concrete with 0% and 50%.	CS Carbonation	The increases in strength of concrete at lower w/b=0.4, carbonation depth increases in GGBS indoor condition.
Adam et. al. (2007)	M 30, w/b= 0.5	GGBS with the replacement of cement with 30%, 50% and 70%	CS and Carbonation	Maximize in strength of GGBS at 50%replacement in OPC And 70% of replacement was increased up to 12 to 15 mm of carbonation depth.
Belie et. al. (2013)	M30, w/b= 0.5	GGBS with the replacement of 50%, 70%, and 85%.	Carbonation	longer curing periods helped limit carbonation in 70% and 85% replacement of cement although not enough to eliminate corrosion risk.
Bezabih et. al. (2021)	M30, w/c= 0.47	GGBS with replacement of 0%, 30%, 50%, and 70%.	Carbonation CS	The replacement of 50% strength was increased and further decreased at a replacement level of 70%. For 28 days the carbonation depth was 2mm for 0% replacement and increased up to 14 mm for 70% replacement.
Xiantang Zhang (2013)	w/b=0.25, 0.3, and 0.35 mix ratio=1:1.3:1.9	GGBS replaces cement with multiples of 15% up to 60%.	Carbonation	The depth of carbonation increased with the increased slag of replacement, and the water-cement ratio decreased carbonation increased.

Pravalika and Venkat Rao (2018)	w/b =0.5, M30	FA Replacement with multiples of 5% to 30%.	CS Carbonation	For the replacement of 15% strength was increased and then gradually decreased. The carbonation depth was 8mm increased to 11mm for a curing period of 28 days.
Cengiz Duran Atis (2002)	M20, w/c=0.28, 0.33 and 0.55.	FA with 0%, 50%, and 70% replacement levels.	Carbonation CS	For 50% replacement Strength was 70.3 MPa and decreased up to 62% for 70% replacement. The replacement of 70% Fly ash concrete exhibited higher carbonation than 50% replacement and ordinary concrete.
Younis et. al. (2011)	M30, w/b=0.6, 0.65	FA with 0%, 30% and 50% of replacement to OPC	Carbonation CS	For 28 days was 35MPa and decreased up to 12% for 30% replacement. The carbonation depths are 20 to 50% lower in the case of water curing than in the case of air curing.
Hussain et. al. (2017)	M30 w/b= 0.35, 0.5 and 0.65	FA as replacement of 0%, 30%, 40%, and 50%.	Carbonation CS	For 28 days compressive strength was 33 MPa and increased up to 6% for 30% replacement of fly ash. The carbonation depth for control concrete was 3mm for 28 days and increased to 8 mm, 11mm and 20 mm for 30%, 40% and 50% of replacement.
Vedran Carevic (2019)	w/b= 0.6, and 0.48 Mix ratio of 1:2.8:3.4	FA is the replacement of 50% cement and 100% replacement of aggregates	CS Carbonation	Compressive strength was 42.7 MPa for OPC, decreased to 2.5% for 100% replacement of aggregates, and further decreased up to 24.5% for 50% replacement of Fly ash. The measured carbonation depth of control concrete, recycled aggregates, and fly ash replacement to cement at different Co_2 concentrations after 28 days showed recycled aggregates and Fly ash concrete had a higher carbonation depth compared with control concrete.
Narasimha and Kavyateja (2020)	Mix ratio of 1:1.1:1.5. w/b=0.3	FA as a constant replacement of 30% and low-heat cement alcofine as a varying replacement in multiples of 4% up to 16%.	Carbonation	Carbonation depth was 17mm for a nominal mix of 30 % Fly ash and 0% Alcofine, decreased up to 35%, 52%, 70%, and 76% for 4%, 8%, 12%, and 16% of low heat cement with constant replacement of Fly ash 30%. Carbonation depth decreases with increases in alcofine replacement
Jitu kujur et. al. (2017)	w/b=0.5,0.6 and 0.7	PPC which contains 25% FA, MD as a replacement in multiples of 5% up to 20%.	CS Carbonation	Compressive strength for 0.5w/b ratio was 24MPa for 0% replacement and increased up to 4%, 20%, and 8% for 5%, 10%, and 15% replacement of marble dust and decreased to 4% for 20% replacement. Carbonation increases with the w/b ratio and

				exposure period.
Bhunia et. al. (2013)	M30 w/b= 0.5	OPC	CS and Carbonation	The increases in strength up to 35 MPa for 28 days Moreover. Carbonation for 2 months is 3 mm increased to 5 mm and 14 mm for 4 and 6 months.
Sakr and Bassuoni (2020)	M30 w/b= 0.4, 0.5 and 0.6.	FA as 20% and 40% replacement to OPC GGBS as replacement of	Carbonation CS	For 28 days compressive strength was 45 MPa and increased up to 25% and 36% for 40% replacement of Fly ash and 60% replacement of GGBS. The carbonation depth was increased to 3.5 mm and 4 mm for 20% and 40% replacement of fly ash and the depth of carbonation was increased to 3.7 mm and 8mm for 30% and 60% replacement of GGBS.
Nahida and Bhat (2020)	w/b=0.45 Mix ratio= 1:2.2:4.3	RHA is the replacement for OPC in multiples of 5% up to 20%.	CS Carbonation	The compressive strength was 29.8 MPa for OPC and increased up to 2.8%, 4.3%, 7%, and 0.5% the replacement of 5%, 10%, 15%, and 20%. The carbonation depth was 1.10mm and increased to 1.7mm, 2mm, 2.3mm and 2.4mm respectively for 5%, 10%, 15%, and 20% replacement of rice husk ash. As the replacement level increases carbonation depth and compressive strength increases.
Chatveera and Lertwattanaruk (2010)	w/b=0.6, 0.7, and 0.8 mix ratio of 1:3:3	RHA is the replacement of 20% and 40%.	CS Carbonation.	Compressive strength was 27.5MPa for 28 days increased up to 6.5% for 20% and decreased up to 2% for 40%, for a 0.6 w/b ratio. Increasing the rice husk ash percentage replacement from 20% to 40% by weight of binder tends to increase the depth of carbonation.
Navdeep Singh (2016)	M30 w/b=0.45	FA 42% replacement to OPC as control mix MN as 10% replacement to control mix	CS Carbonation	Compressive strength was 40 MPa increased up to 7.5% for 25%replacement of aggregate for 28 days. The carbonation depth was 10mm increased to 15mm for 100% replacement of aggregate.
Muduli and Mukharjee (2019**)**	M30 w/b=0.43, mix ratio of 1:1.6:2.9	MN as the replacement in multiples of 50% up to 20%, with 50%, and 100% recycled aggregates.	CS Carbonation	Compressive strength was 40.5MPa decreased up to 1.25% and 6.2% for 15% replacement of metakaolin Carbonation depth was 4mm and increased to 4.7mm and 5.2mm for 50% and 100% replacement of aggregate with 0% of metakaolin. Observed that the concrete mixes with higher carbonation depth exhibit lower compressive strength.

Khalil and Anwar (2014)	w/b=0.4, 0.5 and 0.6	25% FA constant replacement SF as 5% to 15% replacement.	CS Carbonation	Compressive strength for 0.4 w/b nominal mix was 63MPa and decreased to 14% and 4.7%. The carbonation depth was 4mm and increased to 7.3mm, 7.4mm for 25% of fly ash, and 4.2mm and 4.6mm for silica fume replacements.
Jiho Moon (2020)	M40 w/b= 0.36 mix ratio of 1:1.6:2	15% FA, 3.5% SF, and 2% NS as the replacements for OPC	CS Carbonation	Compressive strength was 48MPa and increased up to 2%, 10%, and 12% for 2% nano-silica,15% Fly ash, and 3.5% silica fume replacements. Carbonation depth was increased to 6mm for 15% Fly ash concrete and decreased by 1.5mm and 1.4mm for 3.5% of silica fume and 2% of nano silica replacements.
Ribeiro (2020**)**	M40 w/b=0.5 mix ratio=1:1.6:2.2.	Sugarcane bagasse ash replacement to OPC in multiples of 5% up to 15%.	Carbonation	The carbonation depth was 5 mm and increased up to 40%, 50%, and 80%, for 5%, 10%, and 15% of bagasse ash Concrete containing bagasse ash showed a higher carbonation rate owing to the reduction in the alkaline reserve reducing its lifetime.
Chandradeo (2021)	M30 Mix ratio of 1:3.2:3.0, w/b= 0.57.	BA is the replacement for OPC in multiples of 5% up to 20%.	CS FS Carbonation	The compressive strength for control concrete was 38 MPa and decreased by 3%, 10%, 18%, and 39% for 5%, 10%, 15% and 20% replacement. Flexural strength for control concrete was 4.7 MPa and decreased by 2%, 8%, 15%, and 23% for 5%, 10%, 15% and 20%. The depth of carbonation control concrete for 360 days was 1.8mm and increased to 2mm, 2.8mm, 3mm and 7mm for the replacement of bagasse ash in multiples 5% up to 20%. The carbonation rate increases by increasing SCBA
Eldin et. al. (2022)	M30 w/b=0.5	RHA replacement with multiples of 5% up to 15%, and SS of 1% and 2%.	CS Carbonation	The compressive strength for 28 days was 28 MPa for 0% replacement and decreased up to 22% for 15% replacement. The carbonation depth of control concrete with 1% soap solution was 11mm carbonation depth was decreased to 9.8mm, 9.6mm and increased to 12.6mm for 5%, 10% and 15% with 1% soap solution replacement. The carbonation depth of control concrete was 11mm and decreased to 6.2 mm, 5.18 mm, 4.7 mm and increased to 13.2 mm for 5%, 10% and 15% with 2% soap solution replacement.

Martin et. al. (2017)	w/b=0.6, and 0.53	OPC and 10 different blended cement concrete mixtures containing the additions combine.	CS Carbonation	Compressive strength varied with blended cement mixtures Carbonation depth was increased with blended mixtures.
Sun et.al., (2007)	W/B=0.5	FA 30%, 50%GGBS, 10% MS, and 10% MS as the replacements for OPC.	CS Carbonation	Metakaolin mix exhibited the highest compressive strength, while the pulverized fuel ash mix demonstrated the lowest strength. Carbonation depth increased maximum for 30% replacement of fuel ash than the other mixtures.

**RHA: Rice Husk Ash, B *RHA: Rice Husk Ash, BA: Sugarcane Bagasse ash, SF: Silica Fume, NS: Nano-Silica, MN: Metakaolin, MS: Micro Silica, MD: Marble dust, SS: Soap solution, CS: Compressive Strength, FS: Flexural Strength.*

3.Conclusion

In conclusion, alternative materials like GGBS, fly ash, rice husk ash, and sugarcane bagasse ash offer environmental and economic benefits, their impact on carbonation depth and long-term durability must be carefully considered. Balancing the positive effects on strength and sustainability with the potential for increased carbonation depth is crucial in ensuring the performance and durability of concrete in the long run. Based on the findings from the reviewed literature, the following conclusions can be drawn:

1. **Compressive Strength and Carbonation Depth**: Replacing cement with mineral admixtures, results in increased compressive strength and deeper carbonation.
2. **Water-Cement Ratio**: As the water-cement ratio increases, compressive strength decreases while carbonation depth increases.
3. **Recycled Aggregates**: Replacing natural coarse aggregates with recycled aggregates leads to an increase in carbonation depth.
4. **Curing Method**: Concrete cubes that are air-cured tend to experience a higher rate of carbonation compared to those that are water-cured.
5. **Blended Mixtures**: Using blended mixtures, such as combinations of GGBS, fly ash and other mineral admixtures, leads to improvements in both compressive strength and carbonation depth.

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