Performance of Concrete against Carbonation with Blended Mineral Admixtures

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ABSTRACT

The soaring costs of modern construction are largely driven by the heavy reliance on conventional materials like cement, fine aggregates and coarse aggregates. Among these, cement stands out as a particularly energy-intensive material, playing a major role in greenhouse gas emissions. In response to these environmental and economic challenges, researchers have increasingly turned their attention to sustainable alternatives specifically, the use of industrial and agricultural waste products to partially replace traditional concrete ingredients. Incorporating such waste derived materials can significantly lower energy consumption and reduce the carbon footprint of construction activities. Notable among these substitutes are Ground Granulated Blast-furnace Slag (GGBS), Fly Ash (FA), Rice Husk Ash (RHA), Silica Fume (SF) and Metakaolin (M), which have been successfully employed as partial replacements for cement and sand. These supplementary cementitious materials (SCMs) engage in long-term chemical reactions within the concrete matrix, altering its structural and durability characteristics. This literature review explores how the inclusion of SCMs affects two key performance metrics of concrete: its resistance to carbonation and its compressive strength.

Carbonation in cementitious systems is a coupled physicochemical phenomenon in which atmospheric CO_2 diffuses into the pore solution and reacts with portlandite ($Ca(OH)_2$) to form calcium carbonate ($CaCO_3$). When CO_2 dissolves in the pore fluid, it generates carbonic acid (H_2CO_3), which subsequently reacts with calcium phases according to the sequence $H_2CO_3 + CaO \rightarrow CaCO_3 + H_2O$. This transformation depletes the $Ca(OH)_2$ content, causing the pore-solution pH to drop from its initial 12.5–13 down to values near 9–10, thereby compromising the passive film on steel reinforcement. The introduction of Supplementary Cementitious Materials (SCMs) such as GGBS, FA, RHA, SF and metakaolin refines the capillary pore network reducing critical pore diameters and overall permeability which retards CO_2 ingress and delays the carbonation front. However, the pozzolanic consumption of $Ca(OH)_2$ by SCMs diminishes the concrete's intrinsic alkalinity and buffering capacity, rendering SCM-blended matrices more prone to pH reduction upon carbonation despite their denser microstructure. While the secondary C–S–H formation associated with SCMs typically enhances compressive strength, this densification–alkalinity trade-off necessitates careful optimization to ensure both low-carbon benefits and long-term durability of reinforced concrete elements.

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

1. INTRODUCTION

Several studies have investigated the impact of various supplementary cementitious materials (SCMs) on the compressive strength and carbonation depth of concrete, offering valuable insights into the performance of sustainable concrete mixtures. GGBS (Ground Granulated Blast-furnace Slag), one of the most commonly studied SCMs, has shown mixed effects depending on the percentage of replacement. Yunusa (2017) observed that as GGBS replacement increased beyond 50%, the compressive strength of concrete decreased, with the maximum carbonation depth recorded at 50% replacement under both indoor and outdoor conditions. Similarly, Adam (2007) found that 50% GGBS replacement resulted in the highest compressive strength, while carbonation depth peaked at 70% replacement. Belie (2013) emphasized that extended curing periods helped mitigate carbonation in concrete with 70% and 85% GGBS replacement, although these measures were insufficient to eliminate the risk of steel reinforcement corrosion. Gashaw (2021) reinforced these findings by reporting that 50% GGBS replacement improved compressive strength, but the highest carbonation depth was observed at 70% replacement. Xiantangzhang (2013) added that as the water-cement ratio decreased, carbonation depth increased when GGBS replacement levels increased, highlighting the role of water content in influencing carbonation.

Fly Ash (FA) another widely studied SCM, has also demonstrated its potential as a partial replacement for cement. Pravalika (2018) concluded that the highest compressive strength was achieved at 15% Fly Ash replacement, while carbonation depth was maximized at 30% replacement. Cengiz (2002) corroborated these findings by showing that 50% Fly Ash replacement enhanced strength, whereas carbonation depth increased significantly at 70% replacement. Younis (2011) found that 30% Fly Ash replacement increased compressive strength, with carbonation depth being 20% to 50% lower in water-cured samples compared to air-cured samples. Hussain (2017) further confirmed that the optimal strength occurred at 30% replacement, while carbonation depth was highest at 50% replacement. Verdan (2019) studied mixtures incorporating Fly Ash and recycled concrete aggregates, concluding that increasing the proportion of recycled aggregates reduced strength and increased carbonation depth. Ranga (2020) investigated the effects of 30% replacement with Fly Ash and alccofine, reporting increased compressive strength but a corresponding rise in carbonation depth.

In addition to GGBS and Fly Ash, other materials such as marble dust, bagasse ash, and rice husk ash (RHA) have been evaluated for their effects on concrete properties. Jitu (2017) studied marble dust replacement and concluded that the highest compressive strength was achieved at 15% replacement with a 0.5 water-binder ratio, while the maximum carbonation depth occurred at 20% replacement. Daniel Veras (2020) investigated the effects of bagasse ash and reported that carbonation depth increased with higher replacement levels, peaking at 15%. The study also noted that the increased carbonation rate was due to a reduction in the alkaline reserve, which ultimately compromised the lifespan of the concrete. Chandradeo (2021) confirmed that partial replacement with bagasse ash increased compressive strength while reducing flexural strength and increasing carbonation depth. Nahida (2020) and Chatveera (2010) both reported that maximum compressive strength and carbonation depth occurred at 20% RHA replacement, although Chatveera further noted that carbonation depth was highest at 40% replacement. Elsayed Mohamed (2022) studied the combined effects of rice husk ash and soap solution as partial replacements, concluding that compressive strength decreased with higher replacement levels, while carbonation depth was maximized at 15% RHA and 2% soap solution replacement.

Metakaolin and silica fume, two other effective SCMs, have shown varied impacts on concrete performance. Navdeep (2016) found that replacing 42% Fly Ash and incorporating metakaolin as a partial cement replacement yielded maximum compressive strength and carbonation depth at 25% metakaolin replacement. Rakesh (2019) reported that increasing metakaolin replacement led to a decrease in compressive strength, with mixes exhibiting higher carbonation depth tending to have lower strength. Ehab Ahmed (2014) observed that a mixture containing 25% Fly Ash and 15% silica fume exhibited lower compressive strength and higher carbonation depth. Similarly, Jihomoon (2020) reported that a mixture of 15% Fly Ash, 3.5% silica fume, and 2% nano-silica produced the highest compressive strength and carbonation depth.

Blended mixtures combining multiple SCMs have also been investigated for their effects on concrete properties. Martin (2017) compared 10 different blended concrete mixtures and found that compressive strength varied, while carbonation depth consistently increased with blended mixtures. Sun (2007) studied the effects of incorporating 30% Fly Ash, 50% GGBS, 10% micro silica, and 10% pulverized fuel ash, concluding that metakaolin mixtures exhibited the highest compressive strength, while carbonation depth was maximized at 30% fuel ash replacement.

Overall, these studies highlight that while SCMs enhance the compressive strength and sustainability of concrete, they often increase carbonation depth, potentially compromising the long-term durability of concrete structures. Therefore, optimizing the balance between strength and durability through careful selection and proportioning of SCMs remains a critical area of research for sustainable construction practices

2. METHODOLOGY

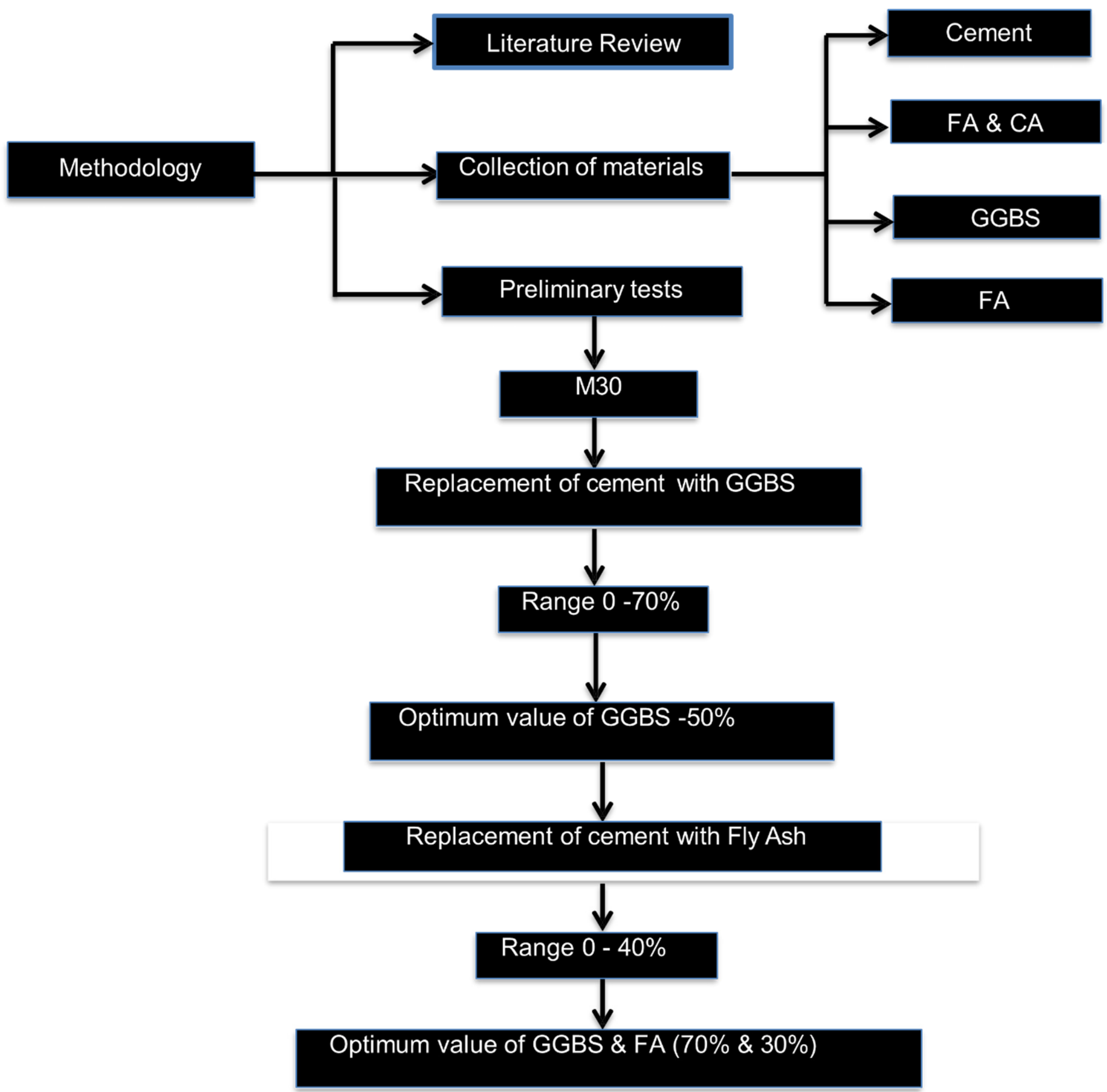
The methodology used to determine the optimal replacement percentage and carbonation depth of cement with GGBS (Ground Granulated Blast-furnace Slag) and Fly Ash in M30 grade concrete involves a systematic process, as illustrated in the corresponding flowchart. The first step involves the selection and preparation of the required materials, including cement, GGBS, Fly Ash, fine aggregate, and a phenolphthalein indicator. Before incorporating these materials into the concrete mix, it is essential to conduct a thorough analysis of their physical and chemical properties to ensure that they meet the necessary quality standards and specifications. The testing of GGBS and Fly Ash is particularly critical, as variations in their chemical composition and particle size can significantly influence the performance of the final concrete mix.

Once the materials have been verified and meet the required standards, the next step is the preparation of the concrete mix by replacing cement with GGBS and Fly Ash in varying proportions. For GGBS, the replacement levels are set at 0%, 10%, 20%, 30%, 40%, 50%, 60%, and 70%, allowing for a comprehensive evaluation of how different percentages impact compressive strength and carbonation depth. Similarly, Fly Ash is used as a replacement for cement in a separate set of mixes, with replacement percentages of 10%, 20%, 30%, and 40%. After mixing, the concrete is cast into the required number of cube specimens to facilitate consistent testing and analysis.

Following the casting process, the concrete cubes are left undisturbed in air for 24 hours to allow for initial setting. After this period, the specimens undergo curing for 3, 7, and 28 days under standard curing conditions. Curing plays a crucial role in ensuring the hydration process is complete, which directly impacts the compressive strength and durability of the concrete. Once the curing period is completed, the cubes are subjected to compressive strength tests to assess the mechanical performance of the different mixes. In addition, carbonation depth is evaluated using a phenolphthalein indicator, which helps determine the extent of carbonation by indicating changes in the pH levels within the concrete matrix.

The evaluation of compressive strength and carbonation depth across different replacement levels of GGBS and Fly Ash provides valuable insights into the impact of these supplementary cementitious materials on the overall performance of M30 grade concrete. By analyzing the results, the optimal replacement percentage of cement with GGBS and Fly Ash can be identified, striking a balance between achieving high compressive strength and minimizing carbonation depth to ensure the long-term durability of the concrete. This systematic approach not only promotes the use of sustainable materials in concrete production but also contributes to reducing the carbon footprint associated with traditional cement usage.

Methodology chart:



An M30-grade concrete mix was prepared to evaluate varying levels of cement replacement with GGBS and fly ash, as outlined in the flowchart. First, all raw materials Cement, GGBS, Fly ash, fine aggregate and a phenolphthalein indicator are gathered and their properties verified. Then, two series of mixtures are cast: one substituting cement with GGBS at 0% - 70% increasing 10% each time by mass, and the other replacing cement with fly ash at 0% -

40% increasing 10% in each replacement. For each replacement ratio, the required number of 150 mm cubes is moulded, left to air-dry for 24 hours and subsequently demoulded. Specimens are cured for 3, 7 and 28 days before testing. After curing, compressive strength is measured and carbonation depth is determined by splitting the cubes, spraying the fresh fracture surfaces with phenolphthalein and recording the uncoloured zone's average depth.

2.0 Materials used:

2.1 Cement

Cement is a binding material used extensively in construction, known for its ability to set, harden, and adhere to other materials, thereby holding them together. Among the various types of cement, Ordinary Portland Cement (OPC) is the most commonly manufactured and widely used around the world due to its reliability and versatility in various construction applications. In this study, OPC of 53 grade, which conforms to the specifications outlined in IS 12269, was used. OPC 53 grade is known for its high strength and durability, making it suitable for structural applications where high compressive strength is required. Its consistent performance and compliance with Indian standards ensure that it meets the necessary quality benchmarks, making it an ideal choice for this research.

Table.1Physical properties of cement

S. No.	Property	Test results
1	Specific gravity	2.94
2	Fineness modulus	6%
3	Consistency	26%
4	Setting time Initial Final	 126 mins. 6 hrs.

2.2 Fine aggregate

Sand is a naturally occurring granular material composed of finely divided rock and mineral particles, commonly consisting of minerals such as quartz, feldspar, mica, and occasionally shell fragments. It is typically classified and sorted based on particle size and shape, making it suitable for various applications depending on the required specifications. In concrete production, sand plays a crucial role as a fine aggregate**,** contributing to the strength, durability, and workability of the mix. In this study, river sand was used as the fine aggregate, conforming to grading zone II as specified in Table 1 of IS 383. River sand, known for its smooth texture and optimal grain size, meets the necessary standards and ensures consistency in the performance of the concrete mix.

Table.2 Physical properties of Fine aggregate

S. No	Property	Test results
1.	Specific gravity	2.58
2.	Fineness modulus	2.63
3.	Unit weight Loose Dense	 1668 kg/m^3 1691 kg/m^3

2.3 Coarse aggregate

The coarse aggregate used in this study was angular in shape, with a maximum nominal size of 10 mm, conforming to the specifications provided in Table 2 of IS 383. Coarse aggregates are defined as materials retained on a 4.75 mm sieve and are commonly derived from crushed stone, gravel, or recycled concrete. The properties of coarse aggregate, including strength and durability, vary based on the type of rock from which they originate. Coarse aggregates are available in various sizes, such as 80 mm, 40 mm, and 20 mm, depending on the application. However, for typical residential and building construction, the maximum aggregate size used is generally 20 mm to ensure ease of mixing, compaction, and structural integrity. In this study, the use of 10 mm coarse aggregate ensures a well-graded mix, contributing to improved workability and strength in the concrete.

Table.3 Physical properties of coarse aggregate

S. No	Property	Test results
1.	Specific gravity	2.84
2.	Fineness modules	6.97%
3.	Unit weight Loose Dense	 1488 kg/m^3 1654 kg/m^3

2.4 Water:

Water plays a crucial role in concrete mixing and curing, significantly influencing the density, strength, and durability of the final mix. It is essential that the water used is clean and free from harmful impurities**,** such as salts and solid particles, as these can negatively affect the concrete's properties. In most cases, potable water is considered suitable for mixing concrete, as it meets the required standards for purity and pH balance. However, the use of seawater for mixing and curing is strictly prohibited due to its high salt content, which can lead to corrosion of reinforcement and reduced durability. The acceptable pH range for water used in concrete is typically between 6.5 and 8, ensuring that the water maintains the desired chemical balance to support proper hydration and strength development.

2.5 Ground Granulated Blast Furnace slag (GGBS)

Blast furnace slag is a by-product generated during the production of pig iron in a blast furnace, where the earthy components of iron ore and limestone flux combine to form slag. When this molten slag is rapidly cooled by quenching it with water in a pond or by using strong water jets, it transforms into granulated slag, which is a fine, granular material that is almost entirely non-crystalline and glassy in nature. Granulated slag possesses latent hydraulic properties, meaning that it can develop cementitious characteristics when mixed with Portland cement and finely processed. The performance and properties of granulated slag, like other materials, are greatly influenced by the parent material from which it originates and the specific manufacturing techniques employed during its production. Due to its excellent binding capabilities and durability, granulated slag has been widely recognized as a valuable supplementary material in concrete, contributing to both improved strength and reduced environmental impact.

Table.4 Physical properties of GGBS		
S. No	**Property**	**Test results**
1.	Specific gravity	2.9
2.	Unit weight Loose Dense	 1150 kg/m^3 1380 kg/m^3

2.6 Fly Ash

Fly ash is a byproduct generated from the combustion of pulverized coal in electric power plants. During the combustion process, the mineral impurities present in the coal, such as clay, feldspar, quartz, and shale, fuse and remain suspended in the exhaust gases. As this molten material rises, it cools and solidifies into spherical, glassy particles, which are then collected as fly ash using electrostatic precipitators or bag filters. Although fly ash appears similar to Portland cement in terms of texture, its chemical composition is distinctly different. When fly ash is introduced into a concrete mix, it undergoes a pozzolanic reaction with the calcium hydroxide (a byproduct released during the reaction between cement and water), forming additional cementitious compounds that enhance the strength and durability of concrete. The degree to which fly ash exhibits cementitious properties varies, depending on its chemical and physical characteristics, as well as those of the cement used in the mix. As a supplementary material, fly ash improves many desirable properties of concrete, including workability, durability, and long-term strength.

Table.5 Physical properties of Fly ash		
S. No	**Property**	**Test results**
1.	Specific gravity	2.56
2.	Unit weight Loose Dense	 1380 kg/m^3 1689 kg/m^3

Chemical composition of Fly Ash and GGBS		
Compound	% content in Fly ash	% content in GGBS
SiO_2	49.45	33.45
Al_2O_3	29.61	13.46
Fe_2O_3	10.72	0.31
CaO	3.47	41.7
MgO	1.3	5.99
Na_2O	0.31	0.16
K_2O	0.54	0.29
TiO_2	1.76	0.84
P_2O_5	0.53	-
Mn_2O_3	0.17	0.40
SO_3	0.27	2.74

3. MIX DESIGN:

Concrete mix design is the process of determining the correct proportions of cement, sand, and aggregates to achieve the desired target strength in concrete structures. The concrete mix can be represented in the ratio format as Concrete Mix = Cement: Sand: Aggregates. In this study, the mix design was carried out for M30 grade concrete using the Indian Standard method (IS 10262 - 2009)**,** which provides guidelines for designing concrete mixes. The mix design process involves a series of calculations and laboratory tests to determine the appropriate proportion of materials that will ensure optimal strength and durability.

Once the correct mix proportions are identified, the materials are carefully measured and placed into the mixing machine. While mixing, the required amount of potable water is added to ensure proper hydration. The fresh concrete mix is then poured into cube molds of 100 mm size in three layers. Each layer is compacted by applying 25 strokes using a tamping rod to remove air voids and ensure uniformity. The top surface of the cubes is leveled and smoothed using a trowel. The specimens are then left undisturbed in moist air for 24 hours to allow initial setting.

After this period, the cubes are cured in clean and fresh water for specified durations of 3 days, 7 days, and 28 days to promote proper hydration and strength development. At the end of the curing period, the specimens are removed from the water and tested for their compressive strength to assess the performance of the concrete mix. This systematic approach ensures that the concrete mix meets the desired strength and durability requirements.

Table. 6 Test data for materials

Mix design	M30(1:2.1:3.1.)
Cement	OPC 53
Aggregate maximum size	10mm
W/C ratio	0.45
Sand corresponds to the zone	Zone -2
Target strength	38.25

Table. 7 Details of Mix design

Water	Cement	Fine aggregate	Coarse aggregate
158 litres	370 kg/m^3	782.36 kg/m^3	1155 kg/m^3
0.45	1	2.1	3.1

4.1 Compressive Strength of concrete

Compressive strength refers to the maximum resistance of concrete to axial loads before failure. To determine this property, compressive strength tests were conducted on concrete cubes of 100 mm size after curing for 3, 7, and 28 days using a compression testing machine.

A total of 72 cubes were prepared for testing. After the initial air curing, the cubes were placed in a curing tank for the specified curing periods. Once the curing period was completed, the cubes were removed from the water and tested. Each specimen was placed in the compression testing machine, and the load was applied at a constant rate of 140 kg/cm^2 per minute until the specimen failed. The maximum load applied at the point of failure was recorded. The compressive strength was then calculated using the formula:

Compressive strength= Load/cross-sectional area

This process ensures an accurate assessment of the concrete's ability to withstand compressive forces.

4.2 Carbonation:

Carbonation of concrete is a chemical process that occurs when carbon dioxide (CO_2) from the atmosphere reacts with the hydration products of cement in the concrete matrix, altering its physical and chemical properties. This phenomenon, commonly known as concrete carbonation, involves the interaction of carbon dioxide with calcium hydroxide ($Ca(OH)_2$), a byproduct of the cement hydration process. The primary chemical reactions involved in carbonation are:

$Ca_2^{+} + 2(OH^{-}) + CO_2 \longrightarrow CaCO_3 + H_2O$ (1)

$CO_2 + Ca\ (OH^{-})_2 \longrightarrow CaCO_3 + H_2O$ (2)

These reactions result in the formation of calcium carbonate ($CaCO_3$), which contributes to changes in the concrete's microstructure. One of the most significant consequences of carbonation is the reduction of the pH in the concrete's pore solution, decreasing it from a high value of around 13 to below 9. This drop in pH destroys the passive oxide film that protects the embedded steel reinforcement, making it susceptible to uniform corrosion, a process known as carbonation-induced corrosion. While carbonated concrete tends to be denser and stronger, the corrosion of reinforcing steel compromises the durability and structural integrity of the concrete. This corrosion can lead to crack formation and ultimately reduce the lifespan of concrete structures, posing serious long-term challenges to their stability and performance.

Carbonation depth measurement:

Carbonation depth measurement is performed using a 1% phenolphthalein solution prepared by dissolving 1 gram of phenolphthalein powder in a mixture of 70 ml of ethanol and 30 ml of de-ionized water**.** To conduct the test, a freshly exposed concrete surface is required. The concrete specimen is placed in a compressive testing machine, where a gradual load is applied until the specimen fails. After the specimen has failed, it is removed from the machine, and phenolphthalein solution is sprayed along the edges of the fractured concrete surface. Upon application, the carbonated portion of the concrete remains colorless, while the non-carbonated portion turns a purple-pink color, allowing for a clear visual distinction between the carbonated and non-carbonated zones. This method effectively helps in determining the depth of carbonation within the concrete structure.

Fig:1 Testing of specimen on CTM

Fig:2 Failure pattern of specimen

Fig .3 Carbonation depth measurement

Fig: 4 Carbonation depth measurement

5. RESULT AND DISCUSSION

The compressive strength of concrete containing mineral admixtures was found to be highest at 50% replacement of GGBS, achieving strengths of 23 MPa, 30.1 MPa, and 45.5 MPa after 3, 7, and 28 days of curing, respectively. Similarly, for Fly ash**,** the maximum compressive strength was observed at 30% replacement**,** with values of 20.5 MPa, 25 MPa, and 41.5 MPa for the same curing periods. However, when these concrete specimens were tested for carbonation depth, it was observed that the rate of carbonation increased with higher replacement levels of mineral admixtures. The maximum carbonation depth for 70% replacement of GGBS was recorded as 7 mm, 8 mm, and 12 mm for 3, 7, and 28 days of curing**,** respectively. Similarly, the maximum carbonation depth for 40% replacement of Fly ash was found to be 6 mm, 8 mm, and 10 mm for the corresponding curing periods. It was also observed that replacing GGBS beyond 50% and Fly ash beyond 30% led to a decrease in compressive strength, indicating that excessive replacement of these admixtures negatively impacts the strength performance of concrete.

Test result graphs of compressive strength:

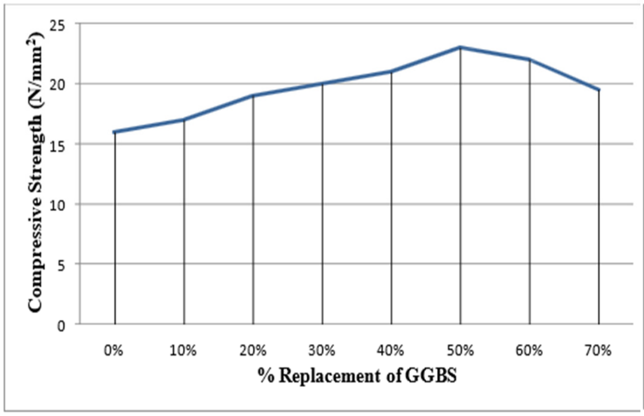


Fig. 5 Three days compressive strength of strength of concrete cube when replaced with GGBS

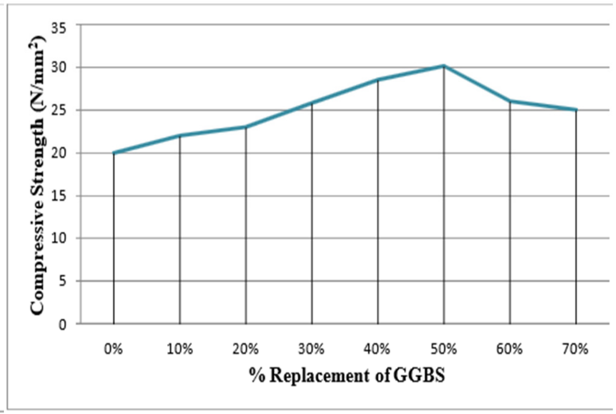


Fig. 6 Seven days compressive strength of strength of concrete cube when replaced with GGBS

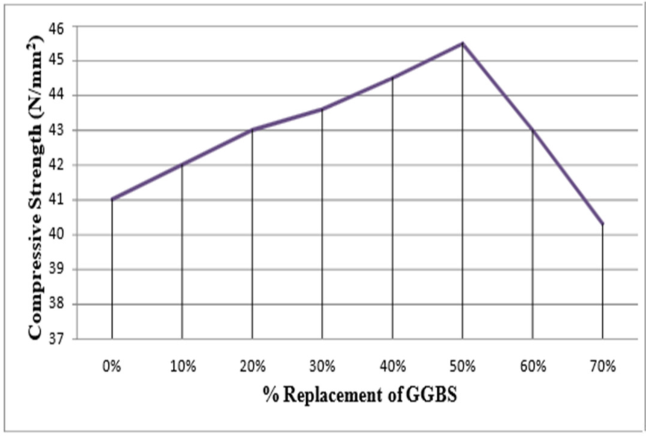


Fig. 7 Twenty-eight days compressive strength strength of concrete cube when replaced with GGBS.

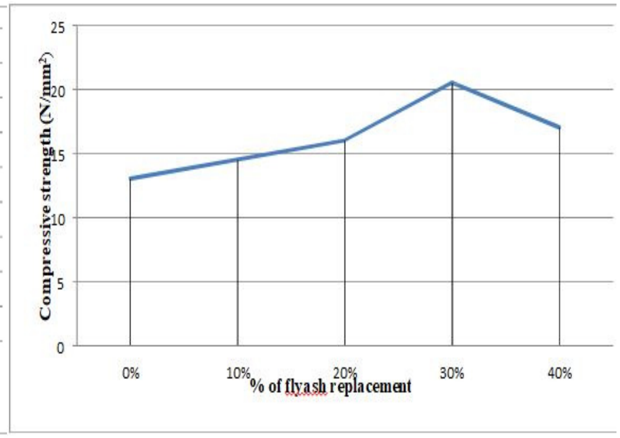


Fig. 8. Three days Compressive strength of concrete when replaced with fly ash.

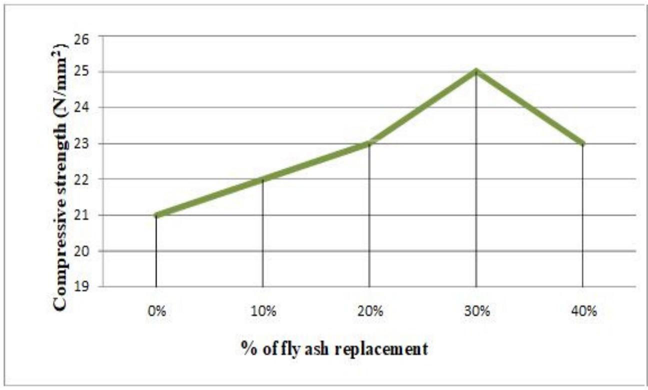


Fig. 9 Seven days compressive strength of concrete cube when replaced with fly ash

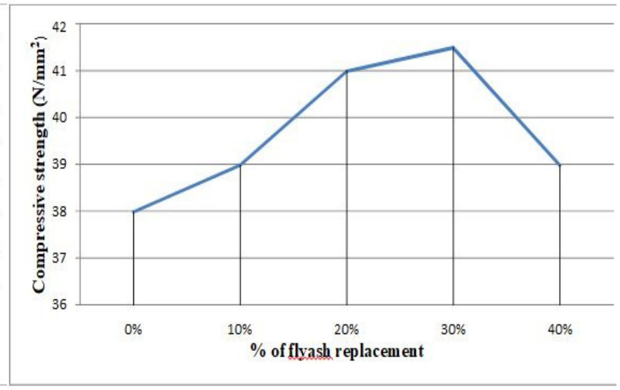


Fig. 10 Twenty eight days compressive strength of concrete when replaced with fly ash

Test result graphs of carbonation depth:

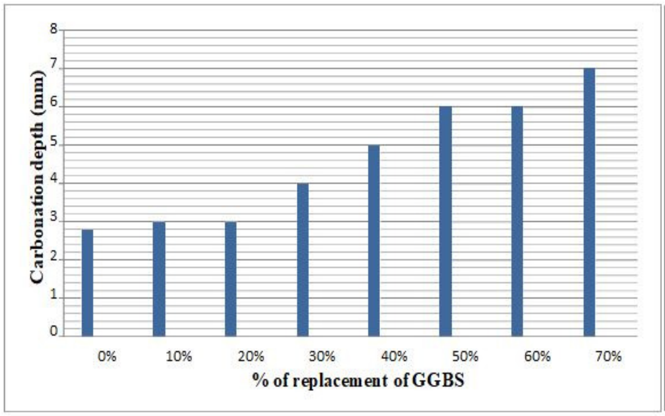


Fig. 11 Carbonation depth at three days with cement replacement with GGBS

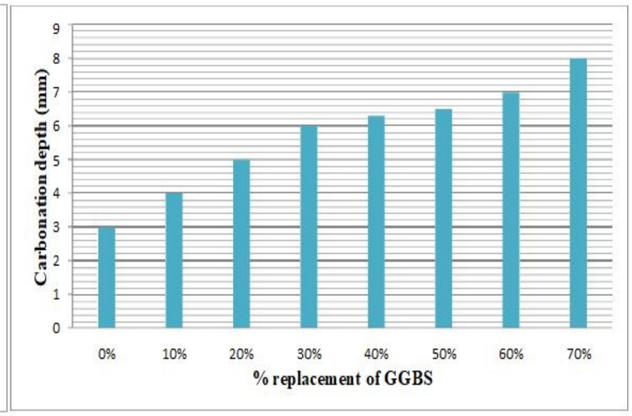


Fig. 12 Carbonation depth at seven days with cement replacement with GGBS

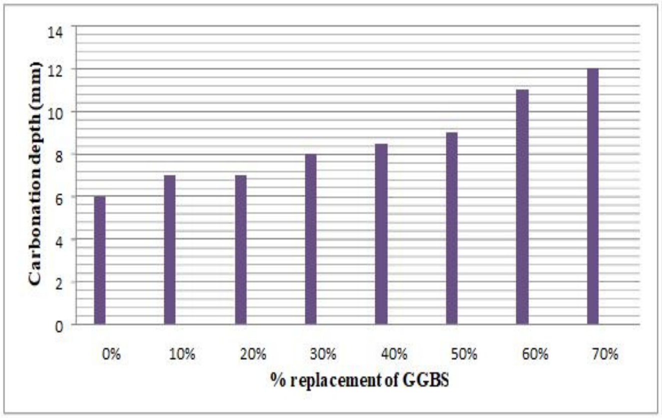


Fig. 13 Carbonation depth at twenty eight days with cement replacement with GGBS

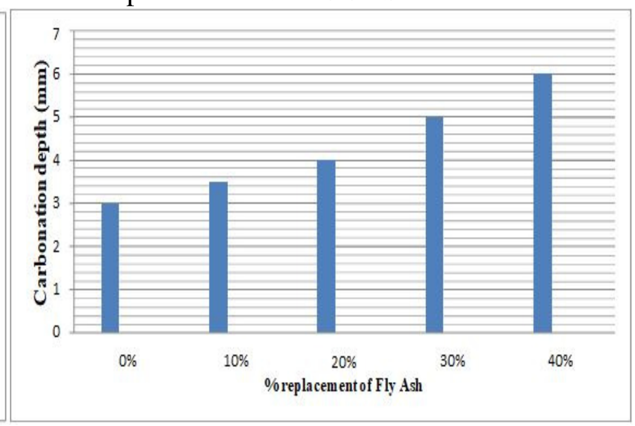


Fig. 14 Carbonation depth at three days with cement replacement with fly ash

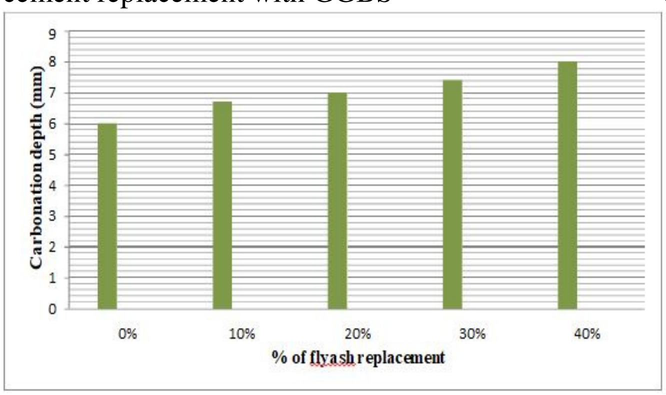


Fig. 15 Carbonation depth at seven days with cement replacement with fly ash

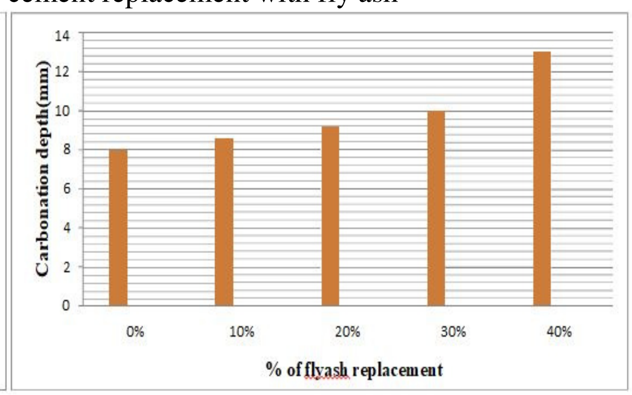


Fig. 16 Carbonation depth at twenty eight days with cement replacement with fly ash

Test result graphs of Workability:

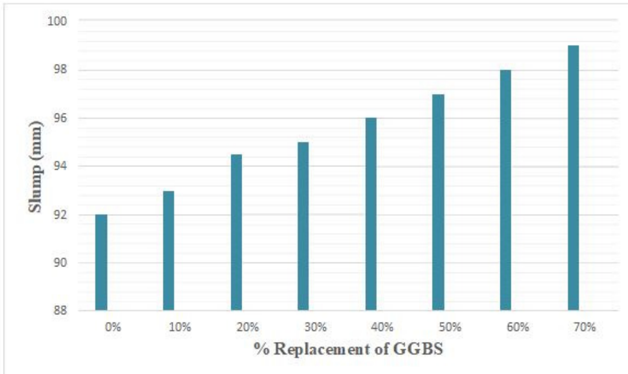
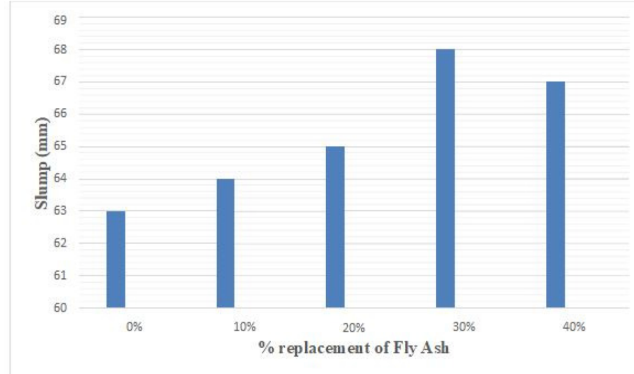
	

Fig. 17 Slump of concrete with cement replacing with GGBS	**Fig. 18** Slump of concrete with cement replacing with Fly ash

6. CONCLUSION

The usage of alternative and waste materials in construction can help reduce environmental impact and lower costs. In this study, the partial replacement of cement with GGBS and Fly ash as different mixtures, GGBS with 50% and Fly ash with 30 % replacement to cement can lead to improved compressive strength. However, the replacement of higher percentages of these alternative materials resulted in a decrease in compressive strength and increases in carbonation depth. The depth of carbonation was minimal with a good compressive strength at 50% Replacement of GGBS and 30% replacement of Fly ash, among these two mixtures of GGBS and Fly ash, GGBS was beneficial to use in construction by this study. GGBS exhibits the highest compressive strength with minimal carbonation depth compared to Fly ash.

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