PERFORMANCE OF CONCRETE WITH MINERAL ADMIXTURES UNDER CARBONATION EXPOSURE: AN EXPERIMENTAL APPROACH

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Abstract

This study investigates the effects of carbonation on the durability and performance of concrete incorporating various mineral admixtures. Mineral admixtures such as fly ash, rice husk ash, ground granulated blast furnace slag (GGBS), and silica fume were used as partial replacements for cement to enhance sustainability and modify the microstructure of the concrete matrix. A series of concrete mixes were prepared with different proportions of these admixtures and subjected to accelerated carbonation conditions. The influence of carbonation on compressive strength, pH variation, and depth of carbonation was systematically analyzed. Results indicated that the inclusion of mineral admixtures influenced the rate of carbonation and the residual strength of concrete, depending on their chemical composition and pozzolanic activity. The study highlights the trade-off between enhanced durability and carbonation susceptibility in modified concrete and provides insights into the optimal use of mineral admixtures for long-term performance in CO_2-rich environments. The incorporation of mineral admixtures significantly enhanced the mechanical properties of concrete compared to conventional mixes.

This study investigates the influence of mineral admixtures—Fly Ash (FA) and Rice Husk Ash (RHA)—on the compressive strength of concrete and its enhancement under controlled CO_2 exposure. A total of sixteen concrete mixes were prepared, incorporating varying percentages of FA and RHA, both individually and in combination. The compressive strength was evaluated before and after 40 hours of CO_2 exposure to assess the effect of accelerated carbonation. The control mix exhibited a strength of 34.56 N/mm², which increased to 42.12 N/mm² upon CO_2 exposure. Notably, the mix with 20% FA showed a strength improvement from 39.40 N/mm² to 46.49 N/mm², while the mix with 20% RHA achieved the highest strength enhancement, rising from 42.64 N/mm² to 48.25 N/mm². Dual replacement mixes, such as 10% FA + 30% RHA and 30% FA + 20% RHA, also showed improved strength performance after carbonation. The results demonstrate that both FA and RHA are effective in enhancing concrete strength, particularly under CO_2 curing conditions. Furthermore, the utilization of these industrial and agricultural by-products contributes to environmental sustainability by reducing cement usage and minimizing waste disposal. This study supports the use of dual mineral admixtures in concrete production as a viable strategy for improving performance and addressing ecological concerns.

Keywords: Fly ash, Rice husk ash, Carbonation

1. Introduction

Carbonation is a technique that can be utilized to sequester CO_2 from the climate in lime or concrete. Carbonation has for some time been believed to be a response that diminishes the toughness of cement. Substantial's surface hardness and strength are impacted via carbonation. Carbonation happens in the pores close to the outer layer of cement and advances to within a substantial component, and is affected by the pore design of the substantial, the relative mugginess and CO_2 focus in the climate, the accessibility of Ca(OH)2 and water, and the utilization of mineral added substances rather than concrete. The microstructure of concrete in the harsh environmental conditions mostly analyzed, and the cause for its lack of durability are also found. Despite its negative impacts on reinforced structures, carbonation benefits in the enhancement of mechanical properties of ordinary plain concrete cannot be overlooked. It is the continuing impact, which causes the surface porosity to diminish. The greenhouse gas CO_2, which is emitted by most cement-based businesses, is absorbed to some extent by concrete structures, aiding in the fight against climate change caused by the greenhouse effect**.**

In the review research that came before this one, a cursory investigation on the effects of carbonation concrete was carried out. To a greater extent than usual, the impact of the additive in the cement was stressed in order to raise the mechanical and strength characteristics. It was discovered that the most favorable qualities of additive proportioned concrete were the compressive test, the flexural test, and the split rigidity test. These tests were all performed on the concrete. The tensile test produced very positive findings, and the corrosive assault on the block demonstrated that the addition of admixture resulted in a smaller decrease in both the material's strength and its mass than would have been expected. During the sulphate assault, there was also a progressive increase in the strength of the addition that was added to the concrete. However, it was considered that admixtures supply higher protection against the more pinkish shade that is formed on the surface of cement. After studying the research work done by a number of different researchers, it has been determined that very little effort has been undertaken to discover the effect of carbon dioxide on the strength and durability properties of concrete as well as treatments to overcome it using mineral admixtures. It has been suggested that research be showed to regulate the characteristics of concrete that has been cured in carbon dioxide gas and that contains a variety of mineral admixtures, such as FA and RHA.

2. Materials

Aggregates

Aggregates, both coarse and fine, are essential constituents in concrete and play a critical role in determining its strength, durability, and overall performance. Typically, coarse aggregates are derived from crushed stone obtained from stone quarries and are required to meet specific gradation and quality standards to ensure proper interlocking and load distribution in the hardened concrete. In this study, coarse aggregates were sourced from a nearby stone quarry and subjected to a series of standard laboratory tests to evaluate their physical properties. These tests included specific gravity, water absorption, impact value, and crushing strength. The results confirmed that the aggregates conformed to the requirements specified in code. The gradation of the aggregates was within permissible limits, making them suitable for use in rigid pavement applications.

Fine aggregates, commonly referred to as sand, were obtained from a natural riverbed. For use in concrete, fine aggregates are free from impurities such as silt, clay, organic matter, and other deleterious substances, as these can adversely affect the bond strength and durability of the concrete. In this research, the river sand was tested for key physical properties including fineness modulus, specific gravity, silt content, and bulk density. These properties were evaluated following the standard procedures outlined in IS: 2386 (Part I & III).

The test results indicated that the fine aggregate was well-graded and free from any significant contamination, thus confirming its suitability for use in the concrete mixes developed for rigid pavement construction. By ensuring the quality and compatibility of both coarse and fine aggregates, the study established a strong foundation for reliable concrete mix design incorporating alternative materials like fly ash and laterite waste.

Cement

In this study, Ordinary Portland Cement (OPC) of 53 grade was used as the primary binding material for the preparation of concrete mixes. The selection of 53-grade cement was based on its high early strength characteristics, which are particularly beneficial in rigid pavement applications where early load-bearing capacity is often desirable. The cement used conformed to the specifications of IS: 12269-2013, which outlines the requirements for 53-grade OPC in terms of chemical composition, physical properties, and performance criteria. A series of standard laboratory tests were conducted to evaluate the physical properties of the cement. The specific gravity of the cement was determined to be 3.16, indicating its suitability for use in concrete mix design calculations, particularly for determining the mix proportions and unit weight of the mix. The standard consistency of the cement was found to be 31%, as determined using the Vicat apparatus in accordance with IS: 4031 (Part 4). This value represents the amount of water required to produce a cement paste of standard consistency, which is essential for assessing setting time and other related properties. Further, the initial setting time of the cement was recorded at 60 minutes, while the final setting time was observed at 320 minutes. These values were obtained through standard procedures as per IS: 4031 (Part 5). The setting time results fall within the permissible limits specified in IS codes, confirming that the cement possesses adequate workability time during mixing, placing, and finishing, as well as sufficient early strength development for rigid pavement construction.

Fly ash

As a supplemental cementitious material, Class F fly ash was used for the purposes of this experiment. This was done according to IS 4082 (1996) and IS 3812 (Part 1) (2003). In this study, 15% of the cement was replaced with fly ash, and the rest of the cement was still used at the same rate.

Rice husk ash

Using rice husk ash as a supplemental cementitious material according to IS 3812 (Part 1) – 2003, this investigation was carried out. In this study, RHA was utilized as a partial substitute for cement at a rate of 15%, with a total replacement rate of 80%.

Water

The water used for concrete work should be potable, i.e., suitable for drinking. The workability and strength characteristics of concrete are significantly influenced by the quality of water used in the mixing process

3. Proportioning of Materials

In this research work, laterite waste was utilized as a partial replacement for coarse aggregates to develop a more economical and sustainable concrete mix compared to conventional concrete. Specifically, replacement levels were selected based on a review of previous studies and preliminary trials. The primary objective was to assess the feasibility of incorporating laterite waste in structural concrete without compromising key mechanical properties.

- Grade of designation: M30
- Type of cement: OPC 43 grade (conforming to IS 12269)
- Maximum nominal size of aggregates :20mm
- Minimum cement content :320 kg/m3
- Maximum W/C ratio :0.50
- Workability :50mm (slump)
- Exposure condition: Mild
- Degree of super vision: Good

- Type of aggregate: Crushed angular aggregate
- Maximum cement content :450 kg/m3
- Mix proportion is 1:1.89:2.86

4. Results

Compressive Strength

Table 1 represents mix proportions considered for test purpose and obtained compressive strength test results for 28 days of curing. Figure 1 represents the graphical representation of the compressive test results.

Table. 1 Mix proportions & Compressive strength test results

Mix Designation	Materials	Compressive strength, N/mm^2
A1	Nominal mix	34.56
A2	Fly Ash (10%)	37.84
A3	Fly Ash (20%)	39.4
A4	Fly Ash (30%)	38.52
A5	Rice Husk Ash (10%)	42.23
A6	Rice Husk Ash (20%)	42.64
A7	Rice Husk Ash (30%)	42.02
A8	Fly Ash (10%) + Rice Husk Ash (10%)	34.45
A9	Fly Ash (10%) + Rice Husk Ash (20%)	34.65
A10	Fly Ash (10%) + Rice Husk Ash (30%)	35.84
A11	Fly Ash (20%) + Rice Husk Ash (10%)	34.71
A12	Fly Ash (20%) + Rice Husk Ash (20%)	34.06
A13	Fly Ash (20%) + Rice Husk Ash (30%)	35.22
A14	Fly Ash (30%) + Rice Husk Ash (10%)	35.24
A15	Fly Ash (30%) + Rice Husk Ash (20%)	35.71
A16	Fly Ash (30%) + Rice Husk Ash (30%)	34.52

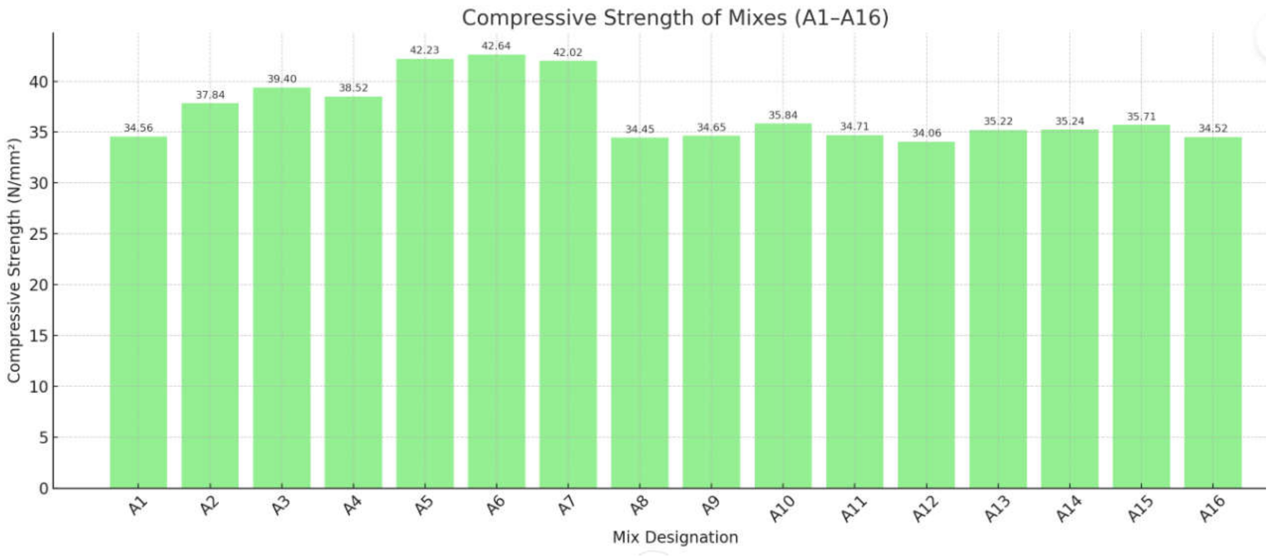

Fig. 1. Graphical representation of compressive strength of various mix proportions

Discussions on compressive strength test results

The compressive strength results for concrete mixes incorporating only Fly Ash (FA) at varying replacement levels (10%, 20%, and 30%) show a clear trend. The highest strength was achieved at 20% FA replacement**,** yielding a compressive strength of 39.4 N/mm² (Mix A3). A slight decline in strength was observed at 30% FA (Mix A4 – 38.52 N/mm²), indicating that increasing FA content beyond 20% may lead to marginal reduction in strength. This suggests that 20% FA replacement provides an optimum balance between pozzolanic activity and cementitious contribution. The maximum compressive strength of 42.64 N/mm² was obtained at 20% RHA replacement (Mix A6). The variation across all three RHA mixes (10%, 20%, and 30%) was relatively narrow, with strengths consistently above 42 N/mm²**.** This indicates that RHA is a highly effective pozzolanic material**,** enhancing compressive strength significantly when used as a partial cement replacement. Concrete mixes containing both FA and RHA in varying proportions (total replacements ranging from 20% to 60%) exhibited a noticeable reduction in compressive strength compared to individual FA or RHA usage: The maximum strength among the combined mixes was recorded for Mix A10 (FA 10% + RHA 30%) at 35.84 N/mm²**,** followed closely by Mix A15 (FA 30% + RHA 20%) at 35.71 N/mm²**.** This performance drop may be attributed to: Dilution of cementitious content, as both FA and RHA are partially replacing cement. Non-synergistic interaction between FA and RHA, which could limit the development of strong binding gels and reduce pozzolanic reactivity. Increased water demand and slower reaction kinetics when both admixtures are present.

The compressive strength results show that incorporating Rice Husk Ash (RHA) at 20% replacement level yields the highest strength (42.64 N/mm²), followed by Fly Ash (FA) at 20% (39.4 N/mm²). However, combining FA and RHA led to a reduction in strength compared to their individual use. These findings suggest that FA and RHA are best utilized independently in concrete for optimal strength enhancement.

Split tensile strength

The Split Tensile Strength Test measures the indirect tensile strength of concrete. Since concrete is weak in direct tension, this test helps assess its crack resistance and tensile load-carrying capacity, which are critical for elements like pavements, slabs. Test is conducted as per IS 5816:1999, and the concrete cylinders of 150 mm diameter × 300 mm height were casted. Type of test is indirect tensile loading by compression along the diameter of the cylinder. Table 2 represents the split tensile test results for 28 days of curing. Figure 2 represents the graphical representation of the split tensile test results

Table 2. Split tensile test results

Mix Designation	Split tensile strength, N/mm2
A1	3.08
A2	3.43
A3	3.88
A4	3.72
A5	3.64
A6	3.82
A7	4.25
A8	4.55

A9	4.74
A10	4.21
A11	4.65
A12	4.25
A13	5.28
A14	5.62
A15	5.44
A16	5.22

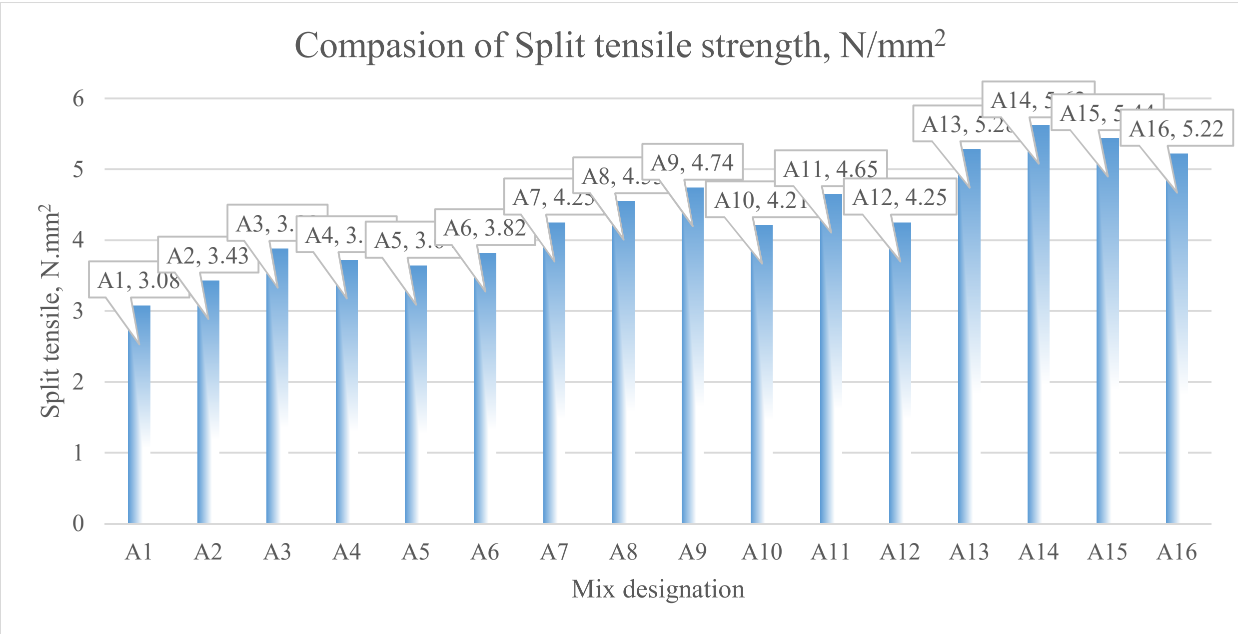

Fig. 2**.** Graphical representation of split tensile strength of various mix proportions

Split Tensile Test

The split tensile strength test results demonstrate a clear improvement in performance across all modified concrete mixes when compared to the nominal mix (A1), which recorded a base strength of 3.08 N/mm²**.** Concrete mixes incorporating Fly Ash (FA) showed enhanced tensile strength with increasing FA content up to 20%. The highest strength in this group was observed at 20% FA (A3) with 3.88 N/mm²**,** followed by a slight decline at 30% FA. This trend mirrors the compressive strength behavior, indicating 20% FA as the optimum level for tensile performance. Mixes containing Rice Husk Ash (RHA) exhibited a steady increase in tensile strength with increasing RHA content. The maximum strength of 4.25 N/mm² was achieved at 30% RHA (A7)**,** confirming RHA's positive influence on tensile properties due to its fine particle size and high silica content. Blended mixes incorporating both FA and RHA exhibited the highest split tensile strengths in the study. These values represent a significant improvement of up to 82% over the nominal mix. Unlike the compressive strength trend—where individual pozzolanic materials performed better—the split tensile results indicate a synergistic effect when FA and RHA are combined. This enhancement can be attributed to improved microstructural packing and increased matrix cohesion from the dual pozzolanic reaction.

The split tensile strength results indicate a significant improvement upon partial replacement of cement with mineral admixtures. The combined use of FA and RHA, particularly in Mix A14 (FA 30% + RHA 10%), yielded the highest strength of 5.62 N/mm², reflecting an 82% increase over the nominal mix. This enhancement may be attributed to the densification of the microstructure and improved interfacial bonding facilitated by the pozzolanic synergy between FA and RHA.

Carbonation of Concrete

Carbonation in concrete is linked to steel reinforcing rusting and shrinking. But it also makes concrete stronger in both compression and tension, so not everything it does to concrete is bad. Carbonation is the process that occurs when carbon dioxide gas dissolves in the pore fluid of concrete and then combines with calcium derived from calcium hydroxide as well as calcium silicate hydrate to produce calcite (CaCO3). Aragonite can be found in places that are hot. Within a few hours or at most a day or two, the CO_2 in the air will have reacted with the surface of the new concrete. The process gradually works its way deeper into the concrete at a pace that is directly proportional to the cube root of the passage of time. Table 3 represents the carbonation effect on compressive strength and Figure 3 represents the graphical representation of the carbonation effects. And Figure 4. Shows graphical representation of the trade of analysis.

Table 3. Carbonation effect on concrete compressive strength

Mix Designation	Materials	Compressive strength, N/mm^2	50 % of CO_2 released in 40 hours
A1	Nominal mix	34.56	42.12
A2	Fly Ash (10%)	37.84	41.05
A3	Fly Ash (20%)	39.4	46.49
A4	Fly Ash (30%)	38.52	42.65
A5	Rice Husk Ash (10%)	42.23	44.25
A6	Rice Husk Ash (20%)	42.64	48.25
A7	Rice Husk Ash (30%)	42.02	45.24
A8	Fly Ash (10%) + Rice Husk Ash (10%)	34.45	44.28
A9	Fly Ash (10%) + Rice Husk Ash (20%)	34.65	41.84
A10	Fly Ash (10%) + Rice Husk Ash (30%)	35.84	42.82
A11	Fly Ash (20%) + Rice Husk Ash (10%)	34.71	41.33
A12	Fly Ash (20%) + Rice Husk Ash (20%)	34.06	41.74
A13	Fly Ash (20%) + Rice Husk Ash (30%)	35.22	41.28
A14	Fly Ash (30%) + Rice Husk Ash (10%)	35.24	41.55
A15	Fly Ash (30%) + Rice Husk Ash (20%)	35.71	42.85
A16	Fly Ash (30%) + Rice Husk Ash (30%)	34.52	42.37

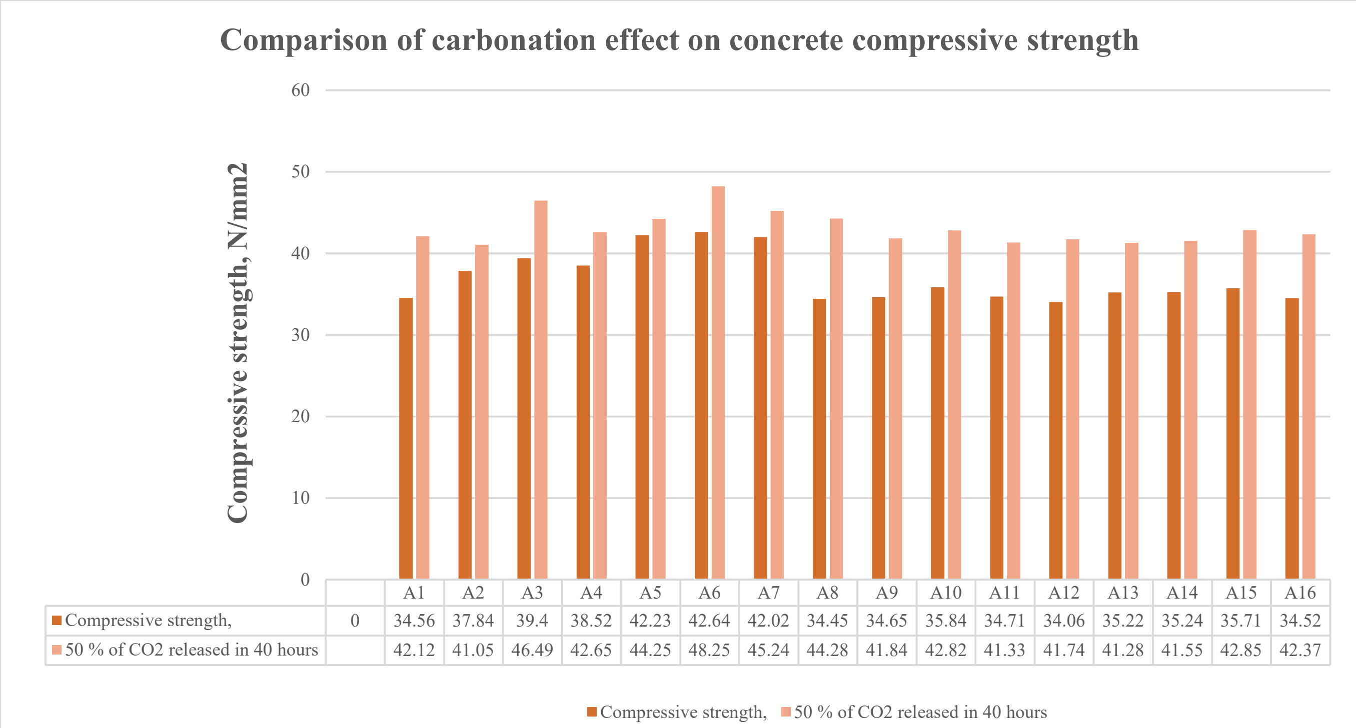

Figure 3. Graphical representation of the carbonation effects

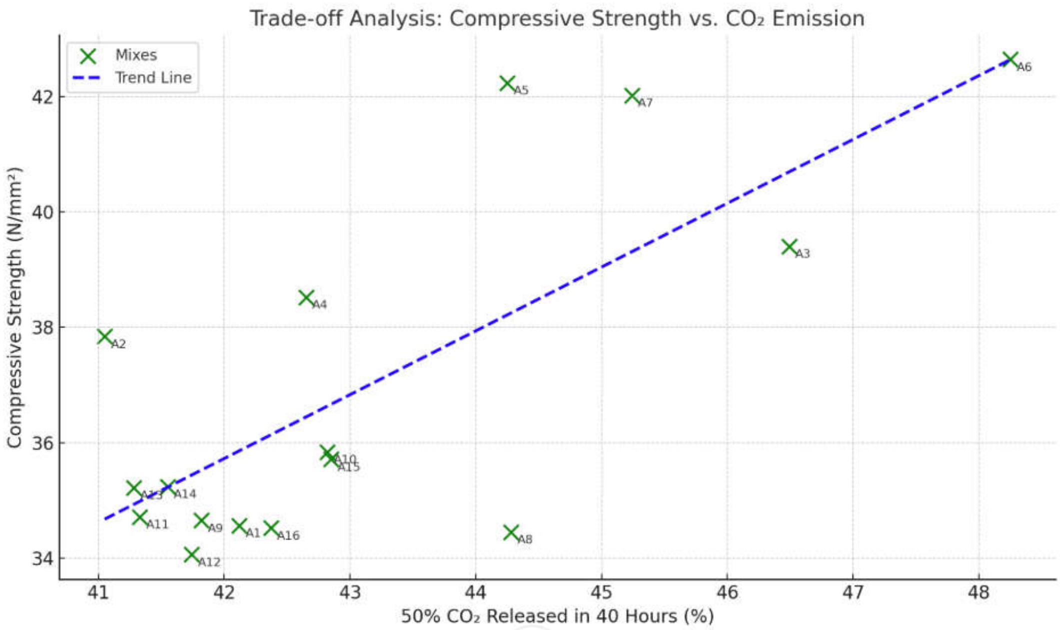

Figure 4. Graphical representation of the trade of analysis

It shows the overall relationship between CO_2 emission and compressive strength. The slight upward slope of the trend line suggests a positive correlation—i.e., higher strength tends to come with slightly higher CO_2 release. Outliers such as A2 (low CO_2, moderate strength) and A6 (high strength, high CO_2) can help identify trade-offs in mix design.

5. Conclusions & Discussions

Based on the experimental results, it was observed that the incorporation of mineral admixtures such as fly ash (FA) and rice husk ash (RHA), both individually and in combination, significantly influenced the compressive strength of concrete. Additionally, the exposure of concrete specimens to carbon dioxide for 40 hours enhanced their mechanical performance, indicating potential benefits of controlled carbonation. The control mix (A1), representing conventional concrete without any mineral admixtures, exhibited a compressive strength of 34.56 N/mm². After 40 hours of CO_2 exposure, the strength increased to 42.12 N/mm², highlighting a notable gain of approximately 22%, likely due to the formation of calcium carbonate through carbonation, which densifies the concrete matrix. The mix containing 20% fly ash (A3) recorded a compressive strength of 39.40 N/mm² under normal conditions. Upon CO_2 exposure, the strength increased further to 46.49 N/mm², marking a significant enhancement. This improvement can be attributed to the pozzolanic reaction of fly ash combined with the effects of carbonation, resulting in a denser and stronger microstructure. Similarly, concrete with 20% rice husk ash (A6) showed the highest initial strength among all mixes at 42.64 N/mm², which further improved to 48.25 N/mm² post-carbonation. This demonstrates the effective reactivity of RHA with lime, forming additional C-S-H gel that contributes to strength development. In the case of dual replacement mixes (fly ash + rice husk ash), moderate improvements in strength were also observed. The combination of 10% FA and 30% RHA (A10) yielded a strength of 35.84 N/mm², which increased to 42.82 N/mm² after CO_2 exposure. The mix with 20% FA and 30% RHA (A13) showed an initial strength of 35.22 N/mm², increasing to 41.28 N/mm² upon carbonation. Another mix with 30% FA and 20% RHA (A15) achieved 35.71 N/mm², which improved to 42.85 N/mm² post-CO_2 exposure. These findings confirm that dual incorporation of fly ash and rice husk ash can be effectively used in concrete production. While individual additions of RHA or FA provided superior strength enhancements, the blended mixes still outperformed the nominal mix after CO_2 exposure, suggesting synergistic benefits under specific conditions. Reducing cement consumption, thereby lowering CO_2 emissions from cement production. Utilizing waste materials, thus mitigating environmental pollution related to fly ash disposal and rice husk burning. Enhancing long-term durability and performance of concrete through controlled carbonation. The study demonstrates that controlled carbonation, in conjunction with the strategic use of fly ash and rice husk ash, can significantly enhance the compressive strength of concrete. This not only contributes to performance improvement but also addresses environmental concerns by reusing industrial by-products effectively. Future research can explore long-term durability, carbonation depth, and microstructural changes to optimize these sustainable mix designs further.

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