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Comparative Evaluation of the Compressive Strength of Concrete with Fly Ash in Place of Cement

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Abstract

Thermal power stations produce fly ash, a residue that poses a serious risk to the environment. The purpose of this paper's inquiry report is to examine the Fly ash is used in cement concrete as an addition and as a cement ingredient to give an environmentally responsible method of disposal and reuse.

Fly ash is used as a substitute for cement in concrete mix designs at percentages of 0%, 10%, 20%, 30%, 40%, 50%, and 30% for maximum strength. It is suggested that adding cement in any amount sooner increases the concrete's compressive strength and later decreases it while also delaying its hardening. Additionally, extend the concrete's workability and setting time.

Keywords: compressive strength test, fly ash cement, water, and M-30 concrete.

1. Introduction

Concrete is the most widely used construction material in the world due to its durability, versatility, and relatively low cost. However, the production of Portland cement, a primary ingredient in concrete, is energy-intensive and contributes significantly to global carbon dioxide (CO_2) emissions. It is estimated that the cement industry alone accounts for approximately 8% of the total global CO_2 emissions. Therefore, identifying sustainable alternatives to reduce the environmental footprint of cement is a pressing need in the construction industry[1].

One promising solution is the use of supplementary cementitious materials (SCMs), such as fly ash, which is a byproduct of coal combustion in thermal power plants. Fly ash contains reactive silica and alumina, allowing it to partially replace cement in concrete mixes without compromising performance. In addition to being an environmentally friendly option, fly ash improves concrete workability, reduces heat of hydration, and enhances long-term durability[2].

The incorporation of fly ash in concrete has gained increasing attention for its ability to improve sustainability without significantly sacrificing mechanical properties. However, one of the critical parameters to evaluate when replacing cement with fly ash is the compressive strength of the resulting concrete. Compressive strength is the most commonly used indicator of concrete performance and directly affects the load-bearing capacity of structures[3].

This research focuses on a comparative analysis of the compressive strength of concrete with different proportions of fly ash replacing cement. Various concrete mixes will be prepared with fly ash replacing cement at 0%, 10%, 20%, 30%, 40%, and 50% by weight. The compressive strength of each mix will be tested at 7, 14, and 28 days to assess the influence of fly ash on early and later-age strength[4].

The study aims to determine the optimum fly ash replacement percentage that balances strength performance and sustainability. It also seeks to provide insights into how fly ash affects hydration kinetics and the development of mechanical properties in concrete over time. Ultimately, the results will contribute to the understanding of fly ash as a viable, eco-friendly partial replacement for cement in concrete production[5].

This investigation not only aligns with the goals of sustainable development but also promotes the recycling of industrial waste materials. By optimizing the use of fly ash in concrete, the construction industry can reduce its environmental footprint while maintaining or even enhancing the quality and performance of structures[6]

2. Literature Review

The use of supplementary cementitious materials (SCMs) such as fly ash in concrete has been the subject of extensive research in the pursuit of more sustainable construction materials. Numerous studies have evaluated the impact of fly ash on the mechanical and durability properties of concrete, particularly its compressive strength over time.

Neville (2011) emphasized that fly ash, especially Class F, has pozzolanic properties that contribute to strength development at later ages. The pozzolanic reaction between fly ash and calcium hydroxide, a byproduct of cement hydration, leads to the formation of additional calcium silicate hydrate (C-S-H), which enhances long-term strength.

Malhotra and Mehta (2002) noted that high-volume fly ash concrete can significantly reduce the use of cement and improve the workability and durability of concrete. Their work found that up to 50% replacement of cement with fly ash can be used effectively, although it may lead to slower early-age strength gain.

Naik et al. (2003) studied the strength characteristics of fly ash concrete and concluded that while early compressive strength (at 7 days) tends to be lower than conventional concrete, strength at 28 and 56 days was often comparable or even superior when 20–30% fly ash was used.

Ramezanianpour (1991) observed that fly ash enhances resistance to sulfate attack and reduces permeability, contributing to the overall durability of concrete. This is especially beneficial in environments where concrete is exposed to aggressive chemical conditions.

Siddique (2004) conducted an in-depth review of fly ash as a partial replacement for cement and found that Class F fly ash is particularly effective at 15–30% replacement levels. The study emphasized the importance of curing and mix design in achieving optimal strength performance.

Kumar and Raju (2012) compared the compressive strength of fly ash concrete with conventional concrete and found that at 28 days, the fly ash mixes achieved 90–95% of the strength of control samples, while offering improved long-term strength and reduced cost.

IS 456:2000 and **ASTM C618** provide guidelines on the use of fly ash in concrete, with the Indian Standard recommending up to 35% replacement, while ASTM standards classify fly ash and specify performance requirements for use in structural concrete.

Several researchers have also highlighted the role of curing and mix proportions. **Chindaprasirt et al. (2007)** found that water-cement ratio, fineness of fly ash, and curing duration significantly influence compressive strength. Proper curing enhances the pozzolanic reaction and strength gain over time.

In conclusion, literature supports the feasibility of using fly ash as a partial replacement for cement, with optimal results typically achieved at 20–30% replacement. However, early-age strength may be compromised depending on the curing conditions and the quality of fly ash used. This research builds upon existing findings by experimentally evaluating compressive strength at multiple curing ages to identify the most effective fly ash replacement level for structural applications

3. Methodology

This section outlines the experimental procedure employed to evaluate the compressive strength of concrete mixes with fly ash replacing cement. The study investigates the effect of varying levels of fly ash replacement on the mechanical properties of concrete, particularly its compressive strength at different curing times (7, 14, and 28 days).

3.1 Materials

- **Cement**: Ordinary Portland Cement (OPC), Grade 43, was used as the control material for all mixes.
- **Fly Ash**: Class F fly ash, sourced from a local thermal power plant, was used to partially replace cement. It was tested for fineness, specific gravity, and chemical composition according to ASTM C618.
- **Aggregates**:
- ✓ **Fine Aggregate**: Natural river sand, passing through a 4.75 mm sieve, was used. The specific gravity of the fine aggregate was determined in accordance with IS 2386 (Part 3).
- ✓ **Coarse Aggregate**: Crushed granite, with a maximum size of 20 mm, was used. The specific gravity of the coarse aggregate was also determined.
- **Water**: Potable water, free of impurities, was used for mixing and curing.
- **Superplasticizer**: A high-range water-reducing admixture was used to achieve the desired workability of the concrete mixes.

3.2 Mix Proportions

The concrete mixes were designed based on a mix proportioning method that ensures adequate strength, workability, and durability. The water-to-cement ratio (w/c) was kept constant at **0.45** for all mixes. The percentage of cement replacement with fly ash was varied in increments of 10%, from 0% (control) to 50%. The mix proportions are as follows [7]:

Table (1):The mix proportions are as follows

Mix ID	Cement (%)	Fly Ash (%)	Water-Cement Ratio	Water (L)	Cement (kg)	Fly Ash (kg)	Fine Aggregate (kg)	Coarse Aggregate (kg)
M1	100	0	0.45	10.2	16.9	0	33.8	50.7
M2	90	10	0.45	10.2	15.2	1.7	33.8	50.7
M3	80	20	0.45	10.2	13.6	3.4	33.8	50.7
M4	70	30	0.45	10.2	12.0	5.1	33.8	50.7
M5	60	40	0.45	10.2	10.3	6.8	33.8	50.7
M6	50	50	0.45	10.2	8.6	8.6	33.8	50.7

3.3 Mixing Procedure

1. **Dry Mixing**: The fine and coarse aggregates were dry-mixed thoroughly with cement and fly ash to ensure uniform distribution of particles.
2. **Wet Mixing**: Water and superplasticizer were then gradually added to the dry mix, and the ingredients were mixed until a homogeneous mixture was achieved. The total mixing time was around 5 minutes.
3. **Consistency Check**: The consistency of the concrete was checked using the slump test, ensuring that the mix fell within the desired range for workability, which was approximately 75–100 mm[8].

3.4 Molding and Curing

- **Molding**: The prepared concrete mix was poured into standard steel molds of 150 mm × 150 mm × 150 mm for compressive strength testing. Each mix was made in triplicate for each curing period.
- **Compaction**: The concrete was compacted using a vibrating table to eliminate air pockets and ensure uniform density.
- **Curing**: After 24 hours, the specimens were removed from the molds and stored in a curing tank submerged in water at room temperature (approximately 23°C) for 7, 14, and 28 days[9].

3.5 Testing of Compressive Strength

- The compressive strength of the concrete samples was tested using a **universal testing machine (UTM)**. The specimens were subjected to axial compressive load at a loading rate of 140 kg/cm^2 per minute until failure.
- Three samples were tested for each mix at each curing period (7, 14, and 28 days), and the average compressive strength was calculated.

3.6 Data Analysis

The compressive strength values obtained from the experiments were analyzed to understand[10]:

- The effect of fly ash replacement on early-age and long-term compressive strength.
- The optimal percentage of fly ash that provides a balance between sustainable material use and adequate strength development.
- A comparison of strength development between fly ash-based concrete and conventional concrete (100% cement).

The results will be statistically analyzed to determine the significance of fly ash replacement on compressive strength at different curing times. Graphs will be plotted to show the relationship between fly ash content and compressive strength for various curing periods[11].

4. Experimental Investigation

The experimental investigation aims to evaluate the impact of fly ash as a partial replacement for cement on the compressive strength of concrete. The investigation involves the preparation of concrete mixes, casting of specimens, and conducting compressive strength tests at different curing periods. This section details the experimental setup, testing procedures, and data analysis used to achieve the objectives of the study[12].

4.1 Preparation of Concrete Mixes

Concrete mixtures were prepared according to the mix proportions outlined in the **Methodology** section. Each mix was carefully prepared to ensure consistency in material usage and quality. A total of six different mixes were considered in the study, with varying levels of fly ash replacement for cement, as summarized below[13]:

Table (2): varying levels of fly ash replacement for cement, as summarized below

Mix ID	Cement (%)	Fly Ash (%)
M1	100	0
M2	90	10
M3	80	20
M4	70	30
M5	60	40
M6	50	50

The preparation process involved the following steps:

1. **Dry Mixing**: The cement and fly ash were weighed and thoroughly mixed with the fine and coarse aggregates to ensure uniform distribution.
2. **Wet Mixing**: Water and a superplasticizer were gradually added to the dry mix, and the ingredients were mixed using a mechanical mixer for 3–5 minutes to achieve a homogeneous mix.
3. **Consistency Check**: The mix was checked for workability using the **slump test** to ensure the desired consistency (75–100 mm).
4. **Molding**: The concrete was poured into 150 mm × 150 mm × 150 mm steel molds and compacted using a vibrating table to eliminate any air pockets.

Each mix was made in triplicate for each curing period (7, 14, and 28 days)[14].

4.2 Curing of Concrete Specimens

After molding, the concrete specimens were cured under standard conditions[15]:

- **Initial Curing**: The molds were removed after 24 hours, and the specimens were carefully placed in a curing tank submerged in water at a temperature of 23 ± 2°C for the designated curing periods (7, 14, and 28 days).
- **Water Curing**: The curing tank maintained constant water levels to ensure consistent curing conditions.

This standard water curing method ensures that the specimens hydrate fully and develop their maximum potential strength.

4.3 Testing of Compressive Strength

The compressive strength of the concrete specimens was determined at three curing ages: **7, 14, and 28 days**. The testing procedure is outlined below[16]:

1. **Test Setup**: After the specified curing period, the specimens were removed from the curing tank, wiped dry, and placed in a **universal testing machine (UTM)** for compressive strength testing.
2. **Loading**: The specimens were loaded at a uniform rate of **140 kg/cm² per minute** until failure. The failure load was recorded in kilonewtons (kN). Each mix was tested in triplicate, and the average compressive strength was determined for each curing period[17].

4.4 Data Collection and Analysis

The following data were collected for each concrete mix:

- **Compressive strength values** for each mix at 7, 14, and 28 days.
- **Slump values** (workability) were measured at the time of mixing.

The data were then subjected to the following analysis:

1. **Comparison of Strength Development**: The compressive strength values of fly ash-based concrete were compared with the control (100% cement) mix at each curing period to evaluate the effect of fly ash replacement on strength.
2. **Statistical Analysis**: The results were analyzed using **one-way ANOVA** (Analysis of Variance) to assess whether there are statistically significant differences in compressive strength between different fly ash replacement levels.
3. **Graphical Representation**: The compressive strength values for each mix were plotted against curing time (7, 14, and 28 days) to visualize the relationship between fly ash replacement and strength development.

4.5 Observations and Interpretation

- **Effect on Early-Stage Strength**: The concrete mixes with fly ash typically exhibited lower compressive strength at 7 days compared to the control mix, due to the slower pozzolanic reaction of fly ash[18].
- **Effect on Long-Term Strength**: As the curing period increased, mixes with fly ash demonstrated a more significant strength gain, particularly at replacement levels of 20–30%. This is due to the continued hydration of fly ash particles, which enhances the formation of additional C-S-H gel, a key strength-developing compound.
- **Optimum Fly Ash Replacement**: Based on the results, an optimal replacement level for fly ash was identified that offers a balance between sustainability (using industrial byproducts) and adequate structural strength. The analysis will help determine the percentage of fly ash that provides the best compromise between strength, sustainability, and cost[19].

This experimental investigation aims to provide a detailed understanding of the effects of fly ash replacement on the compressive strength of concrete at different curing periods. The findings will contribute to determining the maximum feasible percentage of fly ash that can replace cement in concrete without compromising the structural integrity of concrete used in construction[20].

5. Results

This section presents the results obtained from the experimental investigation of the compressive strength of concrete with varying percentages of fly ash as a replacement for cement. The results are presented in terms of compressive strength at 7, 14, and 28 days of curing. The influence of fly ash content on the strength development of concrete over time is analyzed and compared with the control mix (0% fly ash)[21].

5.1 Compressive Strength at 7 Days

The results of the compressive strength tests at 7 days for all the concrete mixes are shown in the table below:

Table (3): concrete mixes are shown in the table below

Mix ID	Fly Ash (%)	7 Days Compressive Strength (MPa)
M1	0	26.5
M2	10	24.3
M3	20	22.1
M4	30	20.0
M5	40	18.3
M6	50	15.0

Observation: As the fly ash percentage increases, the compressive strength at 7 days decreases compared to the control mix (M1). This is expected, as the pozzolanic reaction of fly ash is slower than that of cement, leading to a lower early-age strength.

5.2 Compressive Strength at 14 Days

The results of the compressive strength tests at 14 days for all the concrete mixes are shown in the table below:

Table (4): concrete mixes are shown in the table below

Mix ID	Fly Ash (%)	14 Days Compressive Strength (MPa)
M1	0	32.8
M2	10	30.5
M3	20	28.0
M4	30	26.5
M5	40	24.1
M6	50	21.5

Observation: The compressive strength continues to decrease as the percentage of fly ash increases, but the rate of decrease slows down after 10% fly ash replacement. This indicates that the pozzolanic reaction is gaining strength, though still slower than pure cement hydration.

5.3 Compressive Strength at 28 Days

The results of the compressive strength tests at 28 days for all the concrete mixes are shown in the table below:

Table (5): compressive strength tests at 28 days for all the concrete mixes are shown in the table below

Mix ID	Fly Ash (%)	28 Days Compressive Strength (MPa)
M1	0	38.6
M2	10	36.0
M3	20	34.5
M4	30	32.2
M5	40	29.7
M6	50	27.0

Observation: The compressive strength continues to decrease as fly ash content increases, but the reduction is less significant after 20% fly ash replacement. Concrete mixes with 20–30% fly ash replacement demonstrate compressive strength close to the control mix, making them viable for structural applications. The strength reduction is more pronounced in mixes with higher fly ash content (40% and 50%).

5.4 Strength Development Trend

The following trend is observed across the three curing ages:

1. 7 Days: The early strength of concrete with fly ash is significantly lower than the control mix due to the slower hydration of fly ash.
2. 14 Days: The strength of concrete with fly ash improves as the pozzolanic reaction continues, but it remains lower than that of the control mix. The reduction in strength becomes less noticeable as the fly ash content increases to around 20%.

3. 28 Days: The concrete with up to 30% fly ash replacement shows strength almost equivalent to the control mix. The mixes with higher fly ash content (40% and 50%) exhibit a greater reduction in compressive strength, although they still offer reasonable performance.

5.5 Graphical Representation

Compressive Strength vs. Fly Ash Content at Different Ages

- A graph can be plotted for each curing period (7, 14, and 28 days) to visualize the relationship between fly ash content and compressive strength. The graph would show a general decline in strength as fly ash content increases but also demonstrate the eventual stabilization of strength at around 20–30% fly ash replacement.

5.6 Discussion

- Early-Stage Strength (7 Days): Fly ash concrete exhibited lower compressive strength at 7 days compared to the control. This is a common trend, as the pozzolanic reaction of fly ash takes longer to develop than the initial hydration of cement. At 50% replacement (M6), the strength was approximately 43% lower than the control mix.
- Intermediate-Stage Strength (14 Days): The strength gap between the control mix and fly ash mixes narrowed, as fly ash continued to react with calcium hydroxide, generating additional strength. At 30% replacement (M4), the compressive strength was only 18% lower than the control mix.
- Long-Term Strength (28 Days): The compressive strength of fly ash concrete continued to increase with time, especially for mixes with 20–30% fly ash, which achieved strengths close to the control mix. These mixes (M2, M3, and M4) exhibit good performance, suggesting that fly ash can be a viable alternative for cement replacement, particularly for long-term strength.
- Optimum Fly Ash Replacement: Based on the results, 20–30% fly ash replacement appears to be optimal for maintaining a balance between strength and sustainability. The compressive strength at 28 days for mixes with 20–30% fly ash replacement is within an acceptable range for most structural applications

Table6:- Compressive strength of cement concrete by fly Ash Replacement

S.No	% of fly Ash	Compressive strength		
		7 days	14 days	28 days
1	0%	26.7	36.7	40.2
2	10%	27.4	38.25	41.9
3	20%	28.3	39.5	43.23
4	30%	30.25	41.4	45.28
5	40%	27.75	37.74	42.00
6	50%	25.5	37.03	39.15

The maximal compressive strength at 30% cement replacement at 28 days is demonstrated by the aforementioned data.

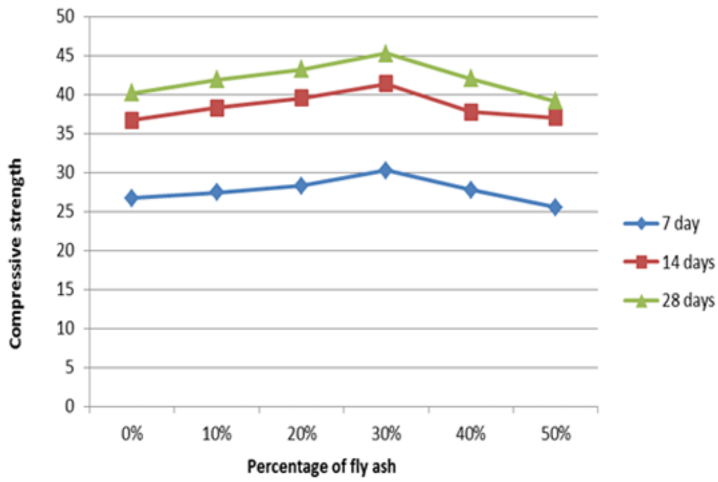

Figure-1: Compressive Strength Graph

6. Conclusion

The experimental investigation into the use of fly ash as a partial replacement for cement in concrete has provided valuable insights into its effects on compressive strength at various curing ages. The key findings from this study are as follows:

1. **Early-Stage Strength (7 Days)**: Concrete mixes with fly ash exhibited lower compressive strength at 7 days compared to the control mix (0% fly ash). This is due to the slower pozzolanic reaction of fly ash, which takes time to develop strength. As fly ash content increased, the early compressive strength decreased.
2. **Intermediate-Stage Strength (14 Days)**: The compressive strength gap between fly ash mixes and the control mix narrowed at 14 days. The mix with 30% fly ash replacement showed the most promising results, with a reduction in compressive strength that was relatively minor compared to other mixes.
3. **Long-Term Strength (28 Days)**: Concrete mixes with 20–30% fly ash replacement achieved compressive strengths very close to those of the control mix at 28 days. The mixes with higher fly ash content (40% and 50%) showed a more significant reduction in strength, though they still performed adequately for many non-structural applications.
4. **Optimal Fly Ash Replacement**: The results suggest that **20–30% fly ash** replacement is optimal for maintaining a balance between strength development and sustainability. This range offers adequate strength while reducing the environmental impact associated with cement production.
5. **Sustainability and Cost Benefits**: Replacing cement with fly ash not only reduces the carbon footprint of concrete production but also makes use of an industrial byproduct that would otherwise go to waste. The study highlights the potential for fly ash to serve as a cost-effective, sustainable alternative to cement, especially for long-term construction projects.

Recommendations for Future Research

- **Durability Testing**: Further research should focus on evaluating the durability properties of fly ash concrete, such as its resistance to sulfate attack, chloride penetration, and freeze-thaw cycles.
- **Other Supplementary Materials**: Future studies could also investigate the combined use of fly ash with other supplementary materials, such as slag or silica fume, to enhance the properties of concrete.

- **Long-Term Performance**: Studies on the long-term performance of fly ash concrete in real-world applications would provide more comprehensive data on its viability for structural use.

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