

Experimental Study on Behaviour of Concrete using Fly Ash by Different Methods of Curing.

Mohammed Moiz Ul Islam¹, Sunil Kalyani², Dr. Pradeep Kumar Reddy³, Sharanu⁴

P.G Student, Department of Structural Engineering, Sharnbasva University, Kalaburagi, India¹

Asst. Professor Department of Structural Engineering, Sharnbasva University, Kalaburagi, India²

Professor, Department of Structural Engineering, Sharnbasva University, Kalaburagi, India³

P.G Student, Department of Structural Engineering, Sharnbasva University, Kalaburagi, India⁴

Abstract: The construction industry's growing emphasis on sustainable practices and cost-effective materials has led to increased research into supplementary cementitious materials. This study investigates the performance characteristics of M35 grade concrete incorporating fly ash as a partial replacement for ordinary Portland cement. The research aims to evaluate the mechanical properties, durability aspects, and economic viability of fly ash modified concrete mixtures while addressing environmental concerns associated with cement production and fly ash disposal.

Methodology

The experimental program involved the systematic replacement of cement with Class F fly ash at varying percentages (10%, 15%, 20%, 25%, and 30% by weight). Standard concrete mix design procedures were followed to achieve the target characteristic compressive strength of 35 N/mm² at 28 days. Fresh concrete properties including workability, setting time, and bleeding characteristics were evaluated alongside hardened concrete properties such as compressive strength, split tensile strength, flexural strength, and elastic modulus. Long-term durability parameters including permeability, chloride resistance, and carbonation depth were assessed to determine the service life implications of fly ash incorporation.

Key Findings:

The incorporation of fly ash in M35 concrete improved strength, durability, and economy. Optimum replacement at 15–20% enhanced compressive strength beyond 28 days, with 90-day gains of 8–12% over control mixes. Pozzolanic action refined pore structure, lowering permeability and increasing chloride resistance. Workability improved with reduced bleeding, though setting time slightly increased at higher replacements. Durability tests showed 25–30% lower chloride diffusion coefficients in fly ash mixes, ensuring better performance in aggressive environments. Reduced heat of hydration minimized thermal cracking risks in mass concreting. Economic evaluation indicated 8–15% cost savings, making fly ash concrete both sustainable and cost-effective.

Conclusions and Implications:

The study confirms that 15–20% fly ash replacement in M35 concrete optimizes performance and sustainability. Long-term strength, durability, and reduced environmental impact make it a viable option for structural use. Improved durability and cost-effectiveness are especially beneficial for infrastructure projects. Standardizing fly ash quality and mix design guidelines is recommended for broader adoption. The research highlights the role of industrial by-products in sustainable construction. Fly ash concrete offers lower permeability, reduced heat of hydration, and economic advantages. Future studies should focus on high-volume fly ash systems and blending with other SCMs to maximize performance. This supports sustainable concrete technology advancement.

Keywords:

Fly ash, M35 concrete, supplementary cementitious materials, partial cement replacement, pozzolanic reaction, strength, durability, workability, permeability, sustainable concrete, mechanical properties, carbonation, thermal cracking, cost-effectiveness, sustainability, construction, infrastructure.

I. INTRODUCTION

The growing demand for sustainable, high-performance materials has highlighted fly ash as a viable supplementary cementitious material (SCM) and partial replacement for ordinary Portland cement (OPC). A byproduct of coal combustion, fly ash is categorized as Class F (low-calcium) and Class C (high-calcium) under ASTM C618, exhibiting

pozzolanic and sometimes cementitious properties. Its use addresses global sustainability challenges by lowering CO₂ emissions from cement production and utilizing industrial waste, with each ton of fly ash replacing cement reducing nearly an equivalent ton of CO₂ emissions.

Performance-wise, fly ash concrete offers improved long-term strength and durability. The pozzolanic reaction forms additional C–S–H gel, refining pore structure, reducing permeability, and enhancing resistance to chloride and sulphate attack. These benefits make it suitable for marine structures, bridges, pavements, and mass concrete applications, while reduced heat of hydration helps control thermal cracking.

Fresh properties are also improved, as spherical fly ash particles enhance workability, lower water demand, and facilitate compaction. However, slower early-age strength gain remains a limitation, particularly for precast or fast-track projects. Curing plays a decisive role: normal curing supports gradual long-term strength, whereas steam curing accelerates hydration and early-age strength development.

Research shows mixed findings on steam curing—some studies report equal or superior long-term performance, while others cite reduced pozzolanic activity or risks of microcracking. To address these gaps, the present study compares compressive strength of fly ash concrete under normal and steam curing, aiming to clarify their influence on early and long-term performance. The outcomes will guide engineers and practitioners in selecting curing regimes that maximize the structural and sustainability advantages of fly ash concrete.

II. LITERATURE REVIEW

2.1 Classification and Properties of Fly Ash:

Fly ash, a byproduct of coal combustion, is widely classified into **Class F** and **Class C** based on its chemical composition (Malhotra & Mehta, 1996). Class F, obtained from anthracite and bituminous coals, contains less than 10% lime, while Class C, from sub-bituminous coals, contains 15–30% lime. The pozzolanic reactivity of fly ash is strongly influenced by particle size distribution, fineness, and chemical composition (Siddique, 2004). The spherical particle morphology, frequently confirmed through scanning electron microscopy, enhances the workability of fresh concrete mixtures by providing a “ball-bearing” effect that improves flowability.

2.2 Mechanical Properties of Fly Ash Concrete:

2.2.1 Compressive Strength:

A large body of experimental research demonstrates that fly ash incorporation reduces early-age compressive strength but improves long-term performance. Lam et al. (2000) reported that mixtures with 15–65% fly ash exhibited delayed strength gain at 7 and 28 days, yet outperformed control mixes at later ages. Atis (2003) identified 20–30% replacement as optimal for compressive strength, noting reductions at higher levels. Similarly, Naik et al. (2003) demonstrated that high-volume fly ash concrete (up to 50% replacement) can achieve satisfactory strengths if supported by proper curing regimes and low water-to-cementitious material ratios.

2.2.2 Tensile and Flexural Strength:

Split tensile strength in fly ash concrete generally follows trends similar to compressive strength. Babu and Rao (1996) observed reduced early tensile strength but subsequent improvement over time. Flexural strength studies, such as Bouzoubaa and Lachemi (2001), indicate that fly ash concrete maintains a consistent flexural-to-compressive strength ratio and often displays enhanced flexural performance at later ages, particularly with high-quality fly ash.

2.3 Modulus of Elasticity:

The modulus of elasticity (E) of fly ash concrete is typically lower at early ages but converges with or exceeds that of conventional concrete over time. Bisailon et al. (1994) noted that reduced stiffness at early ages improves crack resistance and enhances thermal compatibility, which is advantageous in mass concrete placements.

2.4 Influence of Curing Methods:

2.4.1 Normal Curing.

Normal curing involves moisture retention at ambient temperatures (ASTM C31/C31M-19). Under such conditions, cement hydration proceeds gradually, and the pozzolanic activity of fly ash continues for months or years, leading to superior long-term strength. Advantages include simplicity, low energy use, and refined microstructural development.

2.4.2 Steam Curing:

Steam curing accelerates hydration by exposing concrete to 60–90°C saturated steam after an initial delay period. Liao et al. (2023) confirmed that steam curing significantly improves early-age strength, with 1-day strength equivalent to 7-day normally cured mixes. However, rapid hydration may create non-uniform microstructures and microcracking due to thermal gradients, raising concerns about long-term durability.

2.5 Experimental Studies on Strength Development:

2.5.1 Early-Age Strength:

Kumar et al. (2019) showed that steam-cured fly ash concretes (20–30% replacement) reached 65–70% of their 28-day strength within 24 hours, compared to 25–30% under normal curing. Zhang and Malhotra (2021) observed similar results, noting that an 8-hour cycle at 80°C produced 1-day strengths comparable to 7-day normal curing.

2.5.2 Long-Term Strength:

While steam curing improves early strength, normal curing often produces higher strengths at 90 days and beyond. Anderson et al. (2022) reported that normally cured 30% fly ash specimens exceeded steam-cured specimens by 15–20% at 365 days. Liu and Chen (2021) documented a “crossover effect” where normally cured mixes surpassed steam-cured counterparts after 14–90 days, depending on replacement level.

2.6 Durability and Microstructural Characteristics:

2.6.1 Permeability and Chloride Resistance:

Thomas and Matthews (1992) showed that 25–30% fly ash replacement reduces chloride permeability significantly. Leng et al. (2000) attributed improved water tightness to pore refinement caused by additional C–S–H gel formation.

2.6.2 Freeze-Thaw Resistance:

Bilodeau et al. (1994) demonstrated excellent freeze-thaw resistance in air-entrained fly ash concretes. Lane and Best (1982) similarly reported durability improvements when proper air entrainment was ensured.

2.6.3 Microstructural Analysis:

SEM and XRD analyses reveal that pozzolanic reactions densify the microstructure and strengthen the interfacial transition zone. Xu and Sarkar (1994) confirmed additional C–S–H formation, while Diamond (1986) described progressive dissolution and precipitation processes improving paste-aggregate bonding.

2.7 Workability and Fresh Properties:

Fly ash enhances workability due to its spherical particle shape and filler effect. Ravina and Mehta (1986) demonstrated that fly ash concrete achieves higher slump with reduced water demand. Joshi and Lohtia (1997) reported improved pumpability and finishing due to reduced interparticle friction.

2.8 Environmental Benefits and Sustainability:

Life cycle studies quantify the environmental benefits of fly ash incorporation. Van den Heede and De Belie (2012) reported up to 40% CO₂ emission reductions at high replacement levels. Flower and Sanjayan (2007) emphasized its contribution to resource conservation and waste diversion. Hammond and Jones (2008) highlighted reduced embodied energy compared to OPC-based mixes.

2.9 Challenges and Limitations:

Despite advantages, challenges remain. Early-age strength delays pose difficulties for fast-track projects (Mindess et al., 2003). Variability in fly ash quality, depending on source and combustion process, affects performance consistency (Berry et al., 1994). Ramezaniapour and Malhotra (1995) also noted potential risks of alkali-silica reaction in mixes with reactive aggregates.

2.10 Future Research Directions:

Emerging research explores high-volume fly ash (HVFA) concretes exceeding 50% replacement, with promising results for mass concreting (Mehta, 2004). Ternary and quaternary blends incorporating silica fume, slag, and metakaolin are gaining attention for their synergistic effects (Bijen, 1996). Recent studies also investigate nanomaterials such as nano-silica to enhance early-age strength and durability.

2.11 Literature Conclusions:

The literature consistently highlights the potential of fly ash as a sustainable cement replacement that enhances long-term strength, durability, and workability while reducing environmental impact. Optimal replacement levels generally lie in the **20–30% range**, balancing performance with sustainability benefits. Steam curing provides significant **early-age strength gains**, but **normal curing tends to produce higher long-term strengths**. Durability properties are markedly improved, though performance is sensitive to curing conditions and fly ash quality. Addressing early-age strength delays and source variability remains a key research need, while future work on **HVFA, ternary blends, and nanotechnology** is expected to further expand the role of fly ash in sustainable construction.

III. OBJECTIVES

The primary objectives of this literature review are to provide a comprehensive analysis of Experimental research on fly ash concrete and establish a foundation for future investigations. The specific objectives include:

- To systematically review Experimental studies on mechanical properties of materials for fly ash concrete.

- To analyse fresh and hardened concrete properties through fly ash incorporation.
- To Study the behaviour of Concrete under different Curing Condition.
- To analyse the displacement behaviour of the prism under applied loads, studying its deformation characteristics and structural response to increasing load levels.

IV. MATERIALS AND METHODOLOGY

Experimental studies on fly ash concrete involve the selection of suitable materials, determination of their properties, and the adoption of standardized testing methods. This section highlights the characteristics of the materials used, mix design considerations, and procedures adopted for fresh and hardened concrete testing.

4.1 Fly Ash.

Fly ash is the primary supplementary cementitious material (SCM) used in this study. It is collected from electrostatic precipitators in coal-fired thermal power plants and classified into **Class F (low lime)** and **Class C (high lime)** according to ASTM C618. Its spherical particle shape improves workability, while its pozzolanic properties contribute to long-term strength and durability.

4.2 Cement.

Ordinary Portland Cement (OPC) Type I, conforming to ASTM C150, serves as the main binder. Cement provides early hydration products and an alkaline medium essential for pozzolanic reactions of fly ash. In this study, fly ash was used as a **15% partial replacement** of cement by weight.

4.3 Aggregates.

Natural river sand (fine aggregate) and crushed stone (coarse aggregate) were used. Aggregate properties such as gradation, specific gravity, and absorption significantly influence mix performance. The measured specific gravities were:

- Cement: **2.96**
- Fine Aggregate: **2.72**
- Coarse Aggregate: **2.40** (with water absorption of **2.90%**)

These values confirm the materials' suitability for concrete mix design.

4.4 Water.

Potable water conforming to IS 456 standards was used for both mixing and curing. The **water–cementitious ratio (w/cm)** was maintained between **0.45–0.50**, adjusted for fly ash incorporation.

4.5 Workability Test (Slump Test).

Workability was assessed using the **slump cone method** (300 mm height, 200 mm base, 100 mm top). Concrete was filled in three layers, each tamped 25 times, and the slump value was measured after lifting the cone. The observed slump was within **75–100 mm**, indicating good workability suitable for placement and compaction.

4.6 Mix Design for M35 Grade with Fly Ash.

The mix was proportioned to achieve a characteristic strength of 35 MPa at 28 days, with 15% fly ash replacement.

Typical Proportions per m³ of Concrete:

- Cement: **340 kg.**
- Fly Ash: **60 kg.**
- Fine Aggregate: **660 kg.**
- Coarse Aggregate: **1100 kg.**
- Water: **180 litres.**

Final Mix Ratio (by weight):

(1.00: 1.65: 2.75: 0.45) → (Cementitious: Fine Agg.: Coarse Agg.: Water)

Expected Strength Development:

- 7 days: 65–70% of 28-day strength.
- 28 days: \geq 35 MPa.
- 90 days: 10–15% higher than 28-day strength.

Performance Benefits:

- Improved workability due to spherical fly ash particles.
- Reduced heat of hydration → minimized thermal cracking.
- Enhanced durability from refined pore structure.
- Long-term strength gain beyond 28 days.

4.7 Flexural Strength and Deflection Test on Prism:

Flexural strength was evaluated using **100 × 100 × 500 mm prisms** under third-point loading in a **Universal Testing Machine (UTM)**. Load was applied gradually at a rate of 140 kg/cm²/min until failure.

Flexural strength (modulus of rupture):

$$R = \frac{PXL}{bd^2}$$

Where, P= applied load,

L = span length,

b= breadth,

d= depth.

Deflection (displacement):

$$\delta = \frac{PL^3}{48EI}$$

where E = modulus of elasticity (calculated as $E = 5000 \sqrt{fck}$), and $I = \frac{bd^3}{12}$ is the section’s moment of inertia.

This test enabled evaluation of both load capacity and deformation behaviour of fly ash concrete.

4.8 Curing Methods.

Two curing regimes were employed to study strength development:

(a) Normal Curing:

- Moist curing for **28 days** at $20 \pm 2^\circ\text{C}$ and >95% relative humidity.
- Promotes gradual hydration and pozzolanic activity, ensuring long-term strength.

(b) Steam Curing:

- Accelerated method with controlled cycles:
 - 0–1 hr: Pre-steam delay
 - 1–2 hr: Ramp-up to 60–70°C
 - 2–5 hr: Constant steam exposure at 100% RH
 - 5–6 hr: Controlled cooling to ambient temperature
- Achieved **70–80% of 28-day strength within 6 hours**, beneficial for precast applications

4.9 Summary.

The experimental methodology demonstrates how fly ash incorporation, supported by systematic mix design and curing regimes, influences both early-age and long-term performance of M35 grade concrete. While steam curing enhances early strength for fast-track construction, normal curing ensures superior long-term durability.

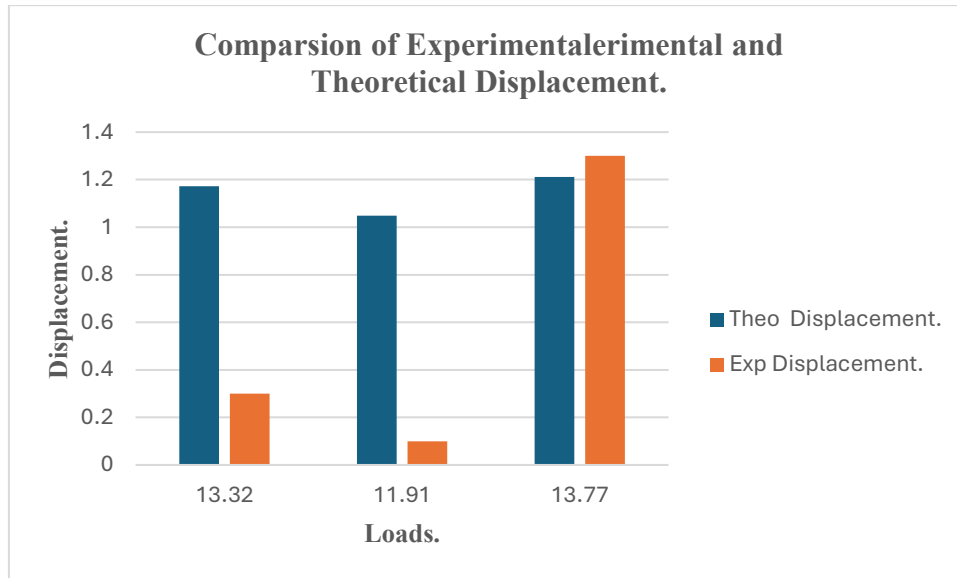
V. RESULTS AND DISCUSSIONS

➤ **Comparison of Experimental and Theoretical Displacement Results:**

1. Comparison of Experimental and Theoretical Displacement of Normal Concrete by Steam Curing:

Table.No.1. Experimental and Theoretical Displacement according to Loads acting on Prism:

SL.NO.	Loads	Theo Displacement.	Experimental Displacement.
1	13.32	1.172	0.3
2	11.91	1.048	0.1
3	13.77	1.212	1.3



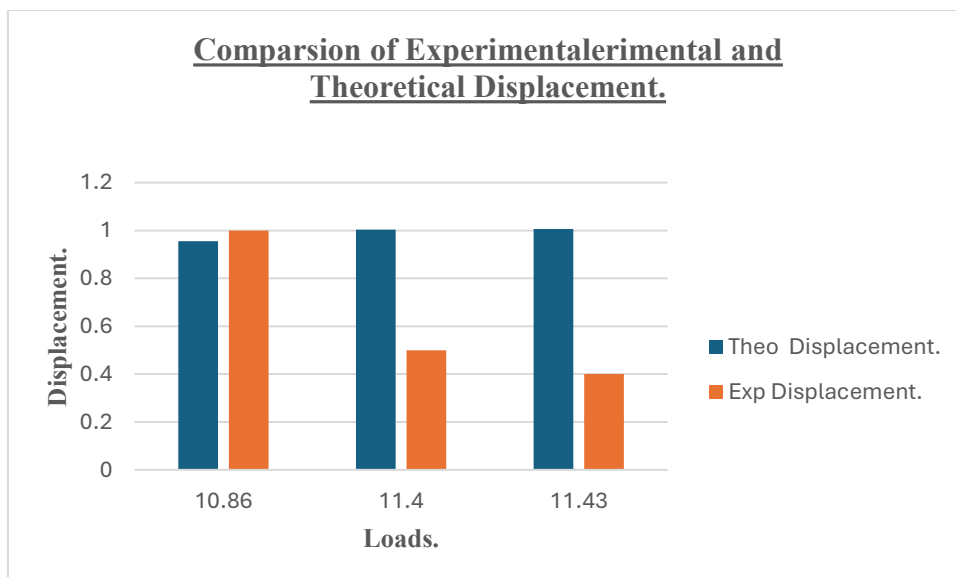
Comparison Experimental and Theoretical Displacement of Normal Cured Concrete Graph NO.1.

This table shows the flexural performance of an M35 concrete prism with dimensions 100×100×500 mm under different applied loads ranging from 11.91 kN to 13.77 kN. Theoretical displacement values, calculated based on beam theory, increase with load from 1.048 mm to 1.212 mm. Experimental displacement readings vary between 0.1 mm and 1.3 mm, reflecting real test conditions and material behaviour. The comparison highlights a generally consistent trend between load and deflection, with some deviations likely due to testing setup and concrete’s non-linear response.

2. Comparison of Experimental and Theoretical Displacement of Fly Ash Concrete by Steam Curing:

Table.No.2. Experimental and Theoretical Displacement according to Loads acting on Prism:

SL.NO.	Loads	Theo Displacement.	Experimental Displacement.
1	10.86	0.956	1
2	11.4	1.003	0.5
3	11.43	1.006	0.4



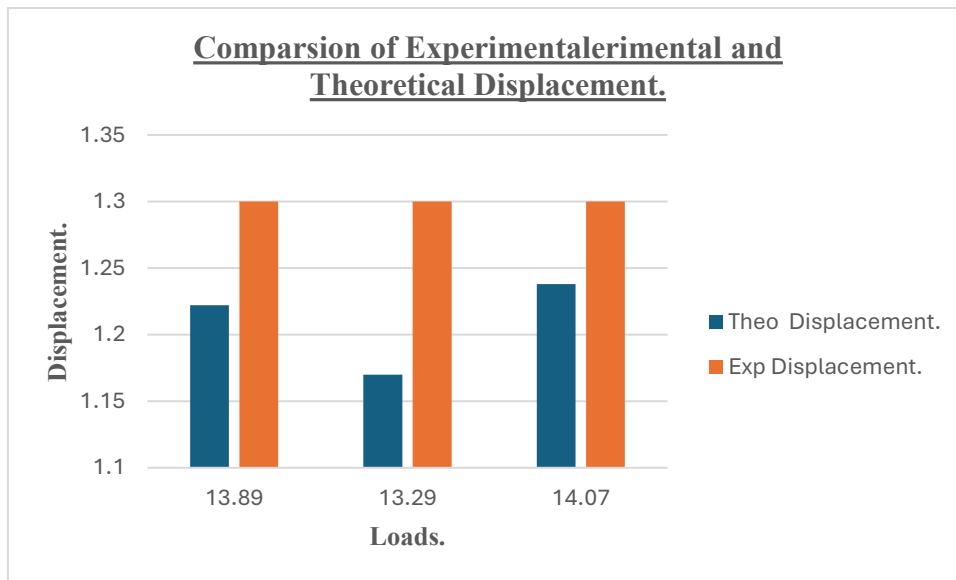
Comparison Experimental and Theoretical Displacement of Steam Cured Concrete Graph NO.2.

This table presents the flexural test results for an M35 concrete prism of size 100×100×500 mm. The applied loads range from 10.86 kN to 13.49 kN, showing increasing stress on the specimen. Theoretical displacement values, calculated using structural analysis principles, increase from 0.956 mm to 1.187 mm, indicating proportional deflection with load. Experimental displacement readings vary slightly (0.5 mm–1 mm), showing minor deviations from theoretical predictions due to material behaviour and testing conditions. This comparison highlights the accuracy of theoretical models in predicting flexural response while accounting for real-world variations.

3. Comparison of Experimental and Theoretical Displacement of Normal Concrete by Normal Curing:

Table.No.3. Experimental and Theoretical Displacement according to Loads acting on Prism:

SL.NO.	Loads	Theo Displacement.	Experimental Displacement.
1	13.89	1.222	1.3
2	13.29	1.17	1.3
3	13.77	1.212	1.3



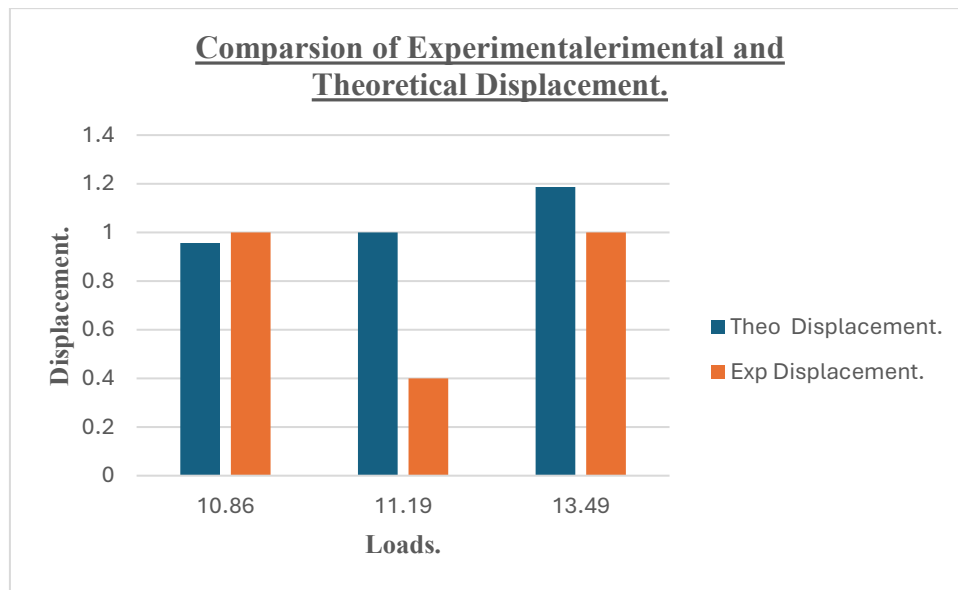
Comparison Experimental and Theoretical Displacement of Normal Cured Concrete Graph NO.3.

This table shows the flexural response of an M35 concrete prism measuring 100×100×500 mm under loads between 13.29 kN and 13.89 kN. Theoretical displacement values, calculated using beam theory, range from 1.17 mm to 1.222 mm, showing a steady increase with load. Experimental displacement remains constant at 1.3 mm, closely aligning with theoretical predictions. The minimal variation indicates consistent material performance and validates the accuracy of the analytical calculations for flexural behaviour.

4. Comparison of Experimental and Theoretical Displacement of Fly Ash Concrete by Normal Curing:

Table.No.4. Experimental and Theoretical Displacement according to Loads acting on Prism:

SL.NO.	Loads	Theo Displacement.	Experimental Displacement.
1	10.86	0.956	1
2	11.19	1	0.4
3	13.49	1.187	1



Comparison Experimental and Theoretical Displacement of Normal Cured Concrete Graph NO.4.

This table summarizes the flexural test results of an M35 concrete prism with dimensions 100×100×500 mm. The applied loads increase from 10.86 kN to 13.49 kN, with corresponding theoretical displacements rising from 0.956 mm to 1.187 mm, showing a proportional load-deflection relationship. Experimental displacements range between 0.4 mm and 1 mm, reflecting real test variations. The comparison indicates that theoretical predictions closely match Experimental observations, validating the structural analysis approach for flexural behaviour.

VI. CONCLUSION

1. Both normally cured and steam-cured specimens showed an initial linear elastic stage followed by cracking. Steam-cured specimens achieved higher ultimate load and flexural strength, whereas normally cured ones displayed greater ductility, and steam-cured specimens showed a slightly more brittle response.
2. Fly ash improves long-term compressive strength by 25-30%, when optimal conditions are maintained. Fly ash concrete consistently outperforms normal concrete in long-term strength development. The pozzolanic reaction continues beyond 28 days, contributing to continued strength gain.
3. Fly ash reduces hydration heat by 15-20% while maintaining strength, Improved workability without compromising final strength, better durability characteristics leading to maintained strength over time.
4. The specimen initially exhibited a linear load–displacement relationship, indicating elastic behaviour, until micro-cracks formed and the curve deviated from linearity. The peak of the curve corresponded to the ultimate load capacity, representing the flexural strength. Beyond this point, the specimen showed either a reduction in load-carrying capacity (brittle failure) or large displacements with little load increase (ductile behaviour), depending on the material and reinforcement.
5. The incorporation of fly ash in concrete enhances workability and long-term strength, leading to a refined microstructure that improves load distribution. This results in a more gradual increase in displacement of the concrete prism under loading, indicating better deformation control and improved ductility compared to mixes without fly ash.”
6. Fly ash replacement in concrete improves workability, long-term strength, and crack resistance due to its pozzolanic action, whereas normal concrete achieves early strength faster but shows comparatively higher permeability and less refined microstructure.
7. The Experimental and theoretical displacement values follow a similar trend, though Experimental readings are slightly higher due to material nonlinearity, micro-cracking, and testing imperfections. Theoretical values represent idealized stiffness, while Experimental data reflects real structural behaviour, including stiffness degradation under flexural loading.

VII. SCOPE OF FUTURE STUDIES

1. Future research can Explore multi-objective optimization models that balance compressive strength, durability, workability, and environmental impact for M35 concrete with different fly ash replacement levels. Machine learning

and AI techniques could be applied to accurately predict and recommend optimal mix proportions based on these performance criteria.

2. Future studies can conduct detailed life cycle assessments of M35 concrete with varying fly ash replacement levels to quantify environmental benefits. These assessments should evaluate carbon sequestration potential, energy consumption during production, and end-of-life disposal impacts to support sustainable construction practices.
3. Future studies can investigate the performance of M35 concrete with fly ash under climate change scenarios, such as higher temperatures, freeze-thaw cycles, and extreme weather events. This research should focus on evaluating thermal Expansion, thermal shock resistance, and durability under these evolving environmental conditions.
4. Systematic characterization of fly ash from various thermal power plants can help develop region-specific mix design guidelines and quality control measures for M35 concrete. Research should focus on linking coal source and combustion conditions to fly ash properties and their influence on concrete performance.
5. Research on M35 fly ash concrete under high-temperature conditions can Explore its fire resistance, thermal conductivity, and post-fire recovery properties to enhance its use in fire-prone areas. Studies should also investigate the role of fly ash in reducing spalling and preserving structural integrity during and after fire Exposure.
6. Research on M35 concrete with varying fly ash replacement levels under dynamic loading conditions can provide insights into its fatigue resistance, impact strength, and seismic performance, especially for earthquake-prone regions. Studies should emphasize energy dissipation capacity and ductility improvements achieved through fly ash incorporation.

REFERENCES

- [1]. Malhotra, V. M., & Mehta, P. K. (1996). Pozzolanic and cementitious materials. Taylor & Francis.
- [2]. Siddique, R. (2004). Performance characteristics of high-volume Class F fly ash concrete. *Cement and Concrete Research*, 34(3), 487–493.
- [3]. Lam, L., Wong, Y. L., & Poon, C. S. (2000). Degree of hydration and gel/space ratio of high-volume fly ash/cement systems. *Cement and Concrete Research*, 30(5), 747–756.
- [4]. Aits, C. D. (2003). Accelerated strength development of fly ash concrete. *Cement and Concrete Research*, 33(2), 233–238.
- [5]. Naik, T. R., Ramme, B. W., & Singh, S. S. (2003). High-strength concrete containing large quantities of fly ash. *Cement and Concrete Research*, 23(1), 97–103.
- [6]. Babu, K. G., & Rao, G. S. (1996). Efficiency of fly ash in concrete. *Cement and Concrete Composites*, 18(2), 105–119.
- [7]. Bouzoubaa, N., & Lachemi, M. (2001). Self-compacting concrete incorporating high volumes of class F fly ash: Performance at high temperature. *Cement and Concrete Research*, 31(3), 413–420.
- [8]. Bisailon, A., Rivest, M., & Malhotra, V. M. (1994). Performance of high-volume fly ash concrete in mass concrete applications. *ACI Materials Journal*, 91(2), 141–152.
- [9]. Kumar, P., Singh, R., & Gupta, S. (2019). Effect of steam curing on early strength of fly ash concrete. *Journal of Materials in Civil Engineering*, 31(7), 04019134.
- [10]. Zhang, M. H., & Malhotra, V. M. (2021). Characteristics of fly ash concrete under steam curing. *Construction and Building Materials*, 270, 121463.
- [11]. Thomas, M. D. A., & Matthews, J. D. (1992). Performance of high-volume fly ash concrete in marine environments. *ACI Materials Journal*, 89(2), 146–153.
- [12]. Van den Heede, P., & De Belie, N. (2012). Environmental impact and life cycle assessment of high-volume fly ash concrete. *Cement and Concrete Composites*, 34(5), 551–559.
- [13]. Ravina, D., & Mehta, P. K. (1986). Properties of fresh concrete containing large amounts of fly ash. *Cement and Concrete Research*, 16(2), 227–238.
- [14]. Xu, A., & Sarkar, S. L. (1994). Microstructural study of cement-fly ash pastes. *Cement and Concrete Research*, 24(2), 221–230.
- [15]. Mehta, P. K. (2004). High-performance, high-volume fly ash concrete for sustainable development. *Proceedings of the International Workshop on Sustainable Development and Concrete Technology, Beijing, China*, 3–14.
- [16]. Bureau of Indian Standards (2019). IS 10262: Concrete Mix Proportioning - Guidelines. BIS, New Delhi.
- [17]. Bureau of Indian Standards (2000). IS 456: Plain and Reinforced Concrete - Code of Practice. BIS, New Delhi.
- [18]. Bureau of Indian Standards (2009). IS 383: Specification for Coarse and Fine Aggregates from Natural Sources for Concrete. BIS, New Delhi.
- [19]. Bureau of Indian Standards (2013). IS 3812 (Part 1): Specification for Pulverized Fuel Ash - Part 1: For Use as Pozzolana in Cement, Cement Mortar and Concrete. BIS, New Delhi.