Improved Pavement Concrete Performance through Partial Cement Replacement with Fly Ash

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Abstract

With the rapid growth of industrial activities, a significant amount of waste materials is being generated, posing serious challenges in terms of environmental impact and land utilization for disposal. Among these industrial by-products, fly ash, produced during coal combustion in thermal power plants, has emerged as a potential resource for sustainable construction. This study explores the use of fly ash as a partial replacement for Ordinary Portland Cement (OPC) in Pavement Quality Concrete (PQC) to enhance both mechanical performance and environmental sustainability.

Cement production is a major contributor to greenhouse gas emissions. As construction demand increases, so does the need for cement. To address this environmental concern, fly ash obtained from Godawari Power & Ispat Ltd. (GPIL), Raipur has been utilized in this study as a substitute for a portion of cement in the concrete mix. The objective is to assess its effectiveness in improving the strength characteristics of pavement concrete while promoting sustainable construction practices.

Experimental investigations were carried out by partially replacing OPC with varying percentages of fly ash, along with the use of a polymer-based superplasticizer to achieve the desired workability and strength. Concrete samples were tested at curing periods of 3, 14, and 28 days. Results indicate that, without superplasticizer, the compressive strength of PQC is inadequate at early and later stages. However, the inclusion of a superplasticizer significantly enhances compressive strength, meeting the performance requirements. Flexural strength was found to be satisfactory even without a superplasticizer, and further improved with its use.

This research confirms that partial replacement of cement with GPIL fly ash, in combination with suitable admixtures, can result in environmentally friendly and structurally efficient pavement concrete.

Keywords: PQC, GPIL Fly Ash, Superplasticizer, Compressive Strength, Flexural Strength, Sustainable Concrete

1. Introduction

1.1 General

Fly ash concrete is widely adopted for its improved durability, strength, and sustainability. As a byproduct of coal combustion in thermal power plants, fly ash reduces the need for Portland cement minimizing CO_2 emissions and promoting green construction. It supports the circular economy by managing industrial waste and conserving natural resources like limestone and clay.

Modern chemical admixtures, such as superplasticizers, enhance the workability of fly ash concrete at low water-cement ratios, improving compressive strength and performance in harsh environments. With superior resistance to chemical attacks and reduced permeability, it is ideal for infrastructure and residential applications, supporting global efforts to lower carbon footprints.

1.2 Fly Ash

Fly ash is a fine gray powder containing silica, alumina, calcium, and iron, generated from coal combustion. Though it has minimal cementitious properties alone, it reacts with cement and moisture to enhance concrete performance.

India’s fly ash generation has surged from 40 million tonnes in 1993-94 to over 300 million tonnes in 2024 due to reliance on coal-based power. Improper disposal causes pollution, soil contamination, and health hazards. Fly ash utilization in construction addresses environmental concerns while promoting sustainability.

As per ASTM C618, fly ash is categorized into:

- **Class F Fly Ash:** Derived from anthracite/bituminous coal; rich in silica and alumina, with low calcium. It has pozzolanic properties and needs cement or lime to harden.
- **Class C Fly Ash:** Produced from sub-bituminous/lignite coal; contains high calcium and exhibits both pozzolanic and self-cementing properties.

Fly ash composition varies by coal type and combustion process, with major oxides (SiO_2, Al_2O_3, CaO, Fe_2O_3) and trace heavy metals. India's MoEF&CC mandates 100% fly ash utilization, encouraging its use in cement, bricks, roads, and soil stabilization.

1.2.1 Class F Fly Ash

Produced from anthracite or bituminous coal; low in lime (under 20%). It has pozzolanic but no self-cementing properties, requiring lime and moisture to form cementitious compounds.

1.2.2 Class C Fly Ash

Formed from lignite or sub-bituminous coal; high in lime (above 20%), sulfates, and alkalis. It is both pozzolanic and cementitious, gaining strength with moisture and capable of replacing more cement than Class F.

1.4 Aim of the Research

Fly ash is generally produced in large quantitities due to increase in power generation capacity. Its production is going to increase further in near future. As its disposal will create problem we need to utilize large amount of fly ash so it is used in cement concrete. A lot of researches show that earlier its replacement was limited to 20-30% but now it is increased to more than 50% replacement. Here focus is mainly on producing concrete with high fly ash replacement and determining various physical properties of material used, flexural and compressive strength of cube and prism.

1.5 Objective and Scope of Work

Fly ash has been used to a certain extent to replace cement in the preparation of concrete for various applications. An attempt has been made in this study to utilize fly ash in varying quantities for the preparation of pavement quality concrete and to study the effect of fly ash on the strength properties of this type of concrete. In this study, fly ash was obtained from Godawari Power & Ispat Ltd. (GPIL), Raipur, a nearby steel manufacturing company.

To achieve the above objective the following scope of work has been planned.

- To determine the physical properties of ingredient materials such as Ordinary Portland Cement (OPC) grade-43, GPIL fly ash, aggregate and sand. .
- To develop mix design for concrete with and without fly ash in varying percentage.
- To perform compressive strength and flexural strength test on both cube and prism specimen for all type of concrete mix samples.
- To study the effect of fly ash replacement on strength characteristics of concrete.

2. Literature Review

2.2 Past Studies on High Volume Fly Ash Concrete

Tan and Pu (1998) they studied the use of supplementary material such as fly ash to improve various properties of concrete like strength and permeability. Being eco friendly it reduces heat of hydration, cost of production, and use of water due to use of admixture. Using admixture also improves the strength of concrete at higher period of curing. Many studies show that use of slag along with fly ash increases the strength.

Marceau (2002) shows that earlier fly ash used in concrete vary between 15% and 25%. It is taken by the mass of the cementitious material. The quantity of fly ash used actually depends on the place of application, fly ash property and the geographic location and climatic condition. Higher percentages of fly ash (30% to 50%) have been used in large structure such as foundations and dam so that it will control the rise in temperature. Many researchers have shown that higher percentage (more than 50%) of fly ash can be used in structures having sound properties and being economical.

Prusinski et al (1993) presented that various things are considered for quantity of fly ash to be used in concrete and the amount of total cementitious material used they are type of fly ash, geographic and climatic condition, qualities of cement, type of admixture used.

2.3 Recent Studies on Fly Ash in Pavement Quality Concrete

In recent years, the utilization of fly ash as a partial cement replacement in pavement quality concrete (PQC) has gained significant traction owing to its environmental benefits and its ability to improve workability and long-term strength.

Mehta and Siddique (2020) reported that Class F fly ash improves the long-term strength development of concrete due to its pozzolanic activity. The study found that up to 30% replacement enhances durability, particularly in sulfate-rich environments.

Gupta et al. (2021) investigated high-volume fly ash concrete mixes (up to 50%) for rigid pavements and concluded that the compressive and flexural strengths at 28 days meet IRC:58 specifications when used with a superplasticizer.

Kumar and Rathi (2022) explored the synergy between fly ash and other mineral admixtures like GGBS and silica fume. Their results indicated a significant reduction in shrinkage and improved flexural strength when fly ash was combined with silica fume.

Li et al. (2023) conducted durability tests on pavement concrete with 20% fly ash replacement and found superior resistance to chloride penetration and freezing-thawing cycles compared to control mixes.

Sharma and Patel (2024) examined the carbon footprint of concrete mixes containing 10-40% fly ash. They highlighted a 25-40% reduction in embodied carbon compared to ordinary Portland cement mixes, positioning fly ash as a sustainable material in pavement applications.

3. Methodology

3.1 Introduction

This chapter provides a detailed description of the experimental work carried out in the present study. It is divided into three sections. The first section deals with the materials used, the second with the tests conducted on these materials, and the third with the mix design procedure.

3.2 Materials

3.2.1 Cement

Ordinary Portland Cement (OPC) of Grade 43 was used in the concrete mixes. It has fine particle size distribution and provides good strength to the structures. The laboratory properties of the OPC 43 Grade used exceed the standard properties specified for this grade.

3.2.2 Fly Ash

Fly ash used in the mix was obtained from Godawari Power & Ispat Ltd. (GPIL), Raipur, and belongs to Class F. It is a fine, grey powder and a byproduct from coal combustion in power plants. Being a pozzolanic material, it exhibits cementitious properties, primarily composed of silica and alumina, contributing to strength, durability, and sustainability of the concrete. Use of fly ash in concrete (commonly called green concrete) is an environmentally friendly practice, reducing CO_2 emissions and addressing disposal issues.

3.2.3 Aggregates

Aggregates, crucial for imparting strength and durability to concrete, were used in two categories:

- **Fine Aggregates**
- **Coarse Aggregates**

Coarse aggregates used had a maximum nominal size of 20 mm.

3.2.4 Admixture

A polymer-based superplasticizer was used to enhance workability without adding excess water. It is light in color and does not alter the appearance of the concrete. It helps reduce water content and increase the final strength.

3.2.5 Water

Potable water was used in the concrete mix. Water plays a critical role in hydration of cement and workability of concrete. The water-cement (w/c) ratio is a crucial factor affecting strength, durability, and workability.

3.3 Tests on Materials

3.3.1 Specific Gravity and Water Absorption

The specific gravity of aggregates indicates their quality. Lower specific gravity implies weaker aggregates. Water absorption gives insight into the porosity of aggregates. The tests were performed as per IS: 2386 (Part III) – 1963.

(a)Coarse Aggregates

Tested using a wire basket:

- Sample size: approx. 2 kg
- Immersed in water for 24 hours
- Weighed in saturated surface-dry and oven-dry conditions

3.3.2 Aggregate Crushing Test

Conducted as per IS: 2386 (Part IV) – 1963.

- Aggregates used: Passed 12.5 mm sieve, retained on 10 mm sieve
- Specimen compacted in three layers in a cylindrical mould
- A compressive load of 40 tons was applied
- Crushed aggregates were sieved through a 2.36 mm sieve

3.3.3 Aggregate Impact Test

Determines the toughness of aggregate under repeated impact, as per IS: 2386 (Part IV) – 1963.

- Aggregates used: Passed 12.5 mm, retained on 10 mm sieve
- Placed in cylindrical mould (diameter 10.2 cm, depth 5 cm) in three layers
- Each layer received 25 tamping blows
- A 13.5–14 kg hammer was dropped from a height of 380 mm for 15 blows

Figure 3.2:-Impact Testing Machine

Table 3.3: Approximate Water Content for Nominal Maximum Size of Aggregate

Nominal Maximum Size of Aggregate (mm)	Suggestive Water Content (kg)
10	208
20	186
40	165

- The table above is for angular coarse aggregate and slump = 20mm ± 5mm and w/c ratio= 0.50.

- The cement content or cementitious material content can be calculated using water to cementitious ratio and water content. The obtained cemetitious content should be less than the maximum cement content i.e. 425 kg/cm^3 and should be greater than minimum cement content of 325 kg/cm^3.

- The volume of coarse aggregate per unit volume of total aggregate is obtained using the table below for which nominal maximum size of aggregate and sand of different zones are required.

Table 3.4: Volume of Coarse Aggregate per Unit Volume of Total Aggregate for Different Zones of Fine Aggregate as per IS: 383

Nominal Maximum Size of Aggregate (mm)	Volume of Coarse Aggregate Per Unit Volume of Total Aggregate for Different Zones of Fine Aggregate			
	Zone IV	Zone III	Zone II	Zone I
10	0.5	0.48	0.46	0.44
20	0.66	0.64	0.62	0.6
40	0.75	0.73	0.71	0.69

The above table valid for water cement ratio of 0.50.With every decrease of 0.05 w/c ratio the ratio of coarse to total aggregate increases by 1 percent.

- All the ingredients are estimated except fine and coarse aggregate content. These two are obtained by determining the volume of water, admixture and cementitious material. Then dividing their mass by their respective specific gravity, multiplying by 1/1000 and subtracting the summation of result from unit volume.

- The mix proportion for concrete is formed for first trial mix.

- The concrete specimens are prepared for compressive strength test as well as for flexural test in the form of cube of 150 x 150 x 150mm and prism of 100 x 100 x 500mm size. The test is performed at 7, 14 and 28 days curing.

- The mix proportion is adjusted till the required strength is achieved from both cube and prism.

4. Result and Discussion

4.1 Introduction

In this chapter all the results of experimental tests on various materials used in Pavement Quality Concrete for cube and prism specimen are presented to improve the mechanical properties. Replacement of cement with fly ash is being done with varying percentage. Polymer based superplasticizer is used in fly ash concrete. The results are discussed in details in the following section.

4.2 Tests Conducted on Cement

Various physical tests are performed on OPC Grade- 43. The results obtained from the tests are given in the following table and not presented for the publication purposes.

Table 4.1: Physical Properties of Cement with Standard Value

Property	**Test Result**	**Standard Value (IS: 12269-1987)**
Fineness (m²/kg)	280	≥225
Standard Consistency (%)	30	28–34
Initial Setting Time (min)	90	≥30
Final Setting Time (min)	220	≤600
Specific Gravity	3.15	3.1–3.2
Soundness (mm)	2	≤10

4.2.1 Compressive Strength Test on Cement

Table 4.2: Compressive Strength Test on Cement

Age of Sample (Days)	**Compressive Strength (MPa)**	**IS Requirement (Min MPa)**
3	28	23
7	42	33
28	53	43

4.3 Tests Conducted on GPIL Fly Ash

The various tests on physical property of Godawari Power & Ispat Ltd. (GPIL), Raipur Fly Ash are conducted. The results obtained are listed below.

Table 4.3: Physical Properties of GPIL Fly Ash with Standard Values

Property	**Value**	**Standard Value (IS 3812-2003)**
Fineness (m²/kg)	310	≥320
Specific Gravity	2.2	2.1–2.6
Lime Reactivity (MPa)	6.5	≥4.5
Loss on Ignition (%)	2.5	≤5

4.3.1 Sieve Analysis on GPIL Fly Ash

For Fly Ash it is performed by Hydrometer Analysis and Particle Distribution Curve is not presented for publication purposes.

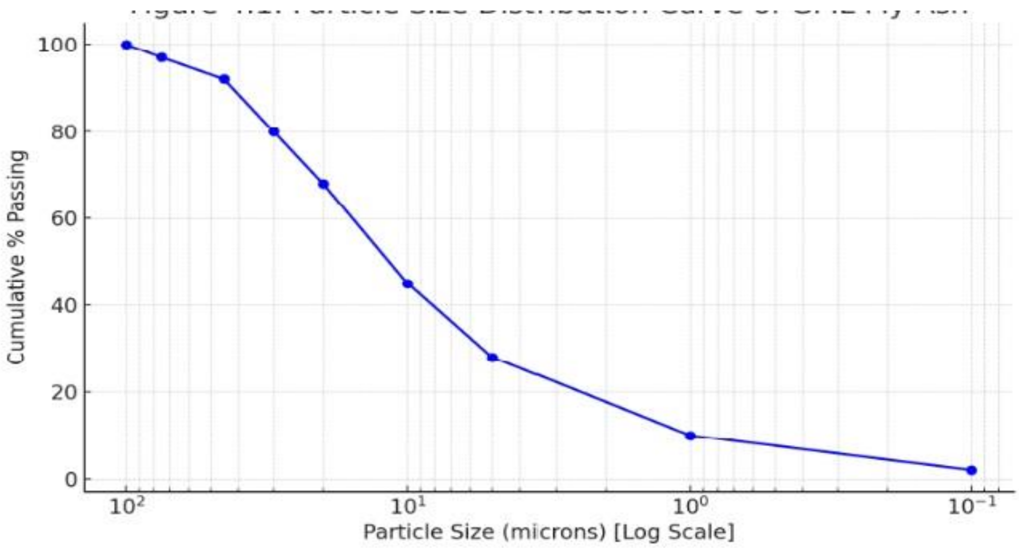

Figure 4.1: Particle Size Distribution Curve of GPIL Fly Ash

4.4 Tests Conducted on Fine and Coarse Aggregate

4.4.1 Water Absorption and Specific Gravity of Aggregates

Table 4.4: Specific Gravity and Water Absorption Value of Coarse and Fine Aggregate

Type of Aggregate	Specific Gravity	Water Absorption (%)
Coarse Aggregate	2.74	0.45
Fine Aggregate	2.61	0.72

4.4.2 Tests Carried out on Coarse Aggregate

Table 4.5: Physical Test Values of Coarse Aggregate

Tests on Coarse Aggregate	Obtained Value	Standard Value
Crushing Value	14.7%	Not more than 30%
Impact Value	14.9%	Not more than 30%
Abrasion Value	22.7%	Not more than 30%
Flakiness Index	9.1%	Not more than 15%
Elongation Index	18.7%	Not more than 15%

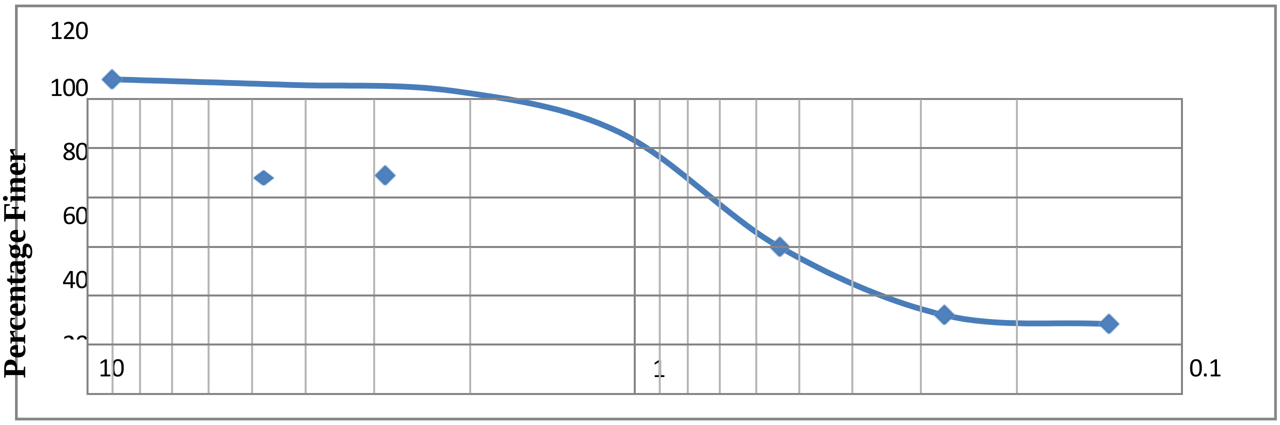

Figure 4.2:-Particle Size Distribution Curve of Fine Aggregate the Sieve Analysis of Fine Aggregate shows that it is well Graded.

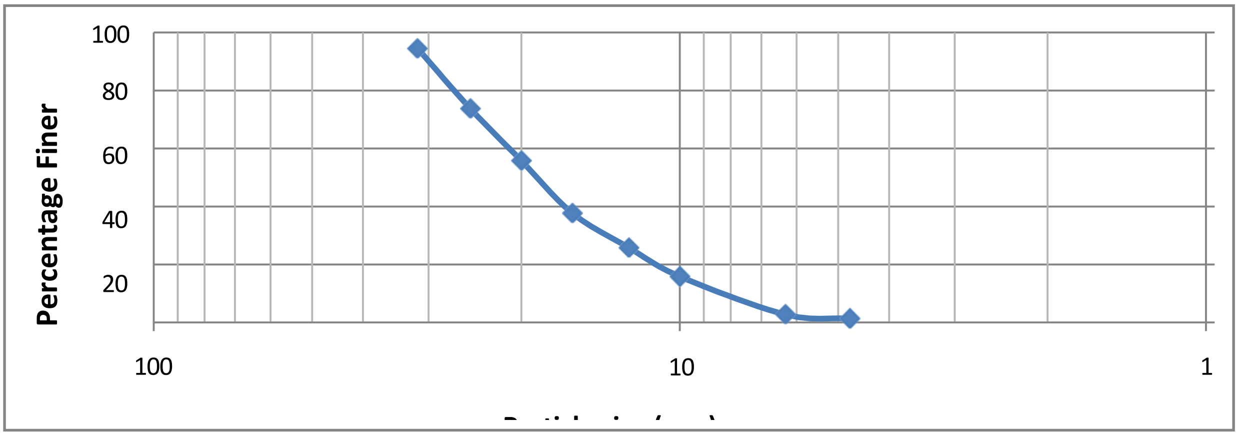

Figure 4.3:-Particle Size Distribution Curve of Coarse Aggregate

The sieve analysis graph shows that coarse aggregate is well graded.

4.5 Mix Design of Concrete

Design of M35 grade of Concrete

In the first trial mix design of M35 is done.

4 cubes and 2 prisms are casted. The compressive strength of concrete in 7, 14 and 28 days was obtained. As the strength obtained at 28 days of cube without any fly ash content is less than the expected strength at 28 days then the mix proportion is redesigned.

Design of M40 grade of Concrete

4 cubes and 2 prisms are casted for 0% replacement and their compressive and flexure strength will be obtained at their respective curing period. Same procedure is adopted for 5% and 10% replacement.

Table 4.6: Compressive Strength (MPa) of M35 and M40 with Fly Ash (0%, 5%, 15%) Without Superplasticizer

Mix ID	Fly Ash (%)	7 Days	28 Days
M35	0	26.1	38.5
M35	5	25.4	36.8
M35	15	22.8	34.2
M40	0	29.2	41.3
M40	5	27.6	39.9
M40	15	24.1	37.5

Table 4.7: Test Results of M35R$_1$ and M35R$_2$ Without Superplasticizer

Mix ID	Fly Ash (%)	7 Days	28 Days
M35R$_1$	10	23.6	35.8
M35R$_2$	20	21.4	33.1

The compressive and flexure strength of concrete cube and prism of 5% and 10% replacement will be carried out after their respective curing periods.

Design of M35 grade of Concrete

In the next trial for M35 the quantity of superplasticizer is further reduce.

Table 4.8: Test Results of M35 R$_1$, M35R$_2$ and M35R$_3$ with Superplasticizer

Mix ID	Fly Ash (%)	7 Days	28 Days
M35R$_1$	10	28.9	41.2
M35R$_2$	20	27.2	38.4
M35R$_3$	25	26.0	36.7

a) *Mixing of Concrete Ingredients*

b) Concrete Mix Filled In Mould

c) Compression Testing on cube *d) Flexure Testing on prism*

e) Failure of Prism *f) Failure of Cube*

Figure 4.4:a) Mixing of Concrete Ingredients, b) Concrete Mix Filled in Mould, c) Compression Testing on Cube, d) Flexure Testing on Prism, e) Failure of Prism And f) Failure of Cube

Table 4.9: Test Results of $M40R_1$, $M40R_2$ and $M40R_3$ with Superplasticizer

Mix ID	**Fly Ash (%)**	**7 Days**	**28 Days**
$M40R_1$	10	30.1	43.8
$M40R_2$	20	28.4	41.0
$M40R_3$	25	27.3	39.2

The design mix of M50 is prepared with reduced water content.

Table 4.10: Test Results of $M50R_1$, $M50R_2$ and $M50R_3$ with Superplasticizer

Mix ID	**Fly Ash (%)**	**7 Days**	**28 Days**
$M50R_1$	10	34.5	48.2
$M50R_2$	20	32.7	46.1

M50R$_3$	25	30.4	43.3

The design of fly ash concrete is prepared with varying percentage of fly ash on M40grade of concrete.

Table 4.11: Test Results of M40 with 5%, 10% and 15% Fly Ash Replacement

Mix ID	**Fly Ash (%)**	**28 Days Flexural Strength (MPa)**
M40R$_1$	5	4.6
M40R$_2$	10	4.8
M40R$_3$	15	5.0

Table 4.12: Test Results of M50 with 5%, 10% and 20% Fly Ash Replacement

Mix ID	**Fly Ash (%)**	**28 Days Flexural Strength (MPa)**
M50R$_1$	5	5.1
M50R$_2$	10	5.3
M50R$_3$	15	5.5

5. Conclusion

5.1 Introduction

This chapter covers the conclusion of the experimental work carried on Pavement Quality Concrete (PQC) having certain percentage of fly ash. The scope for future work on PQC with fly ash is also discussed in this chapter.

5.2 Conclusion

a) The compressive strength of normal concrete increases with the addition of superplasticizer, indicating improved workability and densification.

b) Concrete mixes incorporating fly ash show significant enhancement in both compressive and flexural strength when combined with superplasticizer, making them suitable for structural and pavement applications.

c) The flexural strength results confirm that Pavement Quality Concrete (PQC) containing fly ash can meet the performance requirements, offering a sustainable and economical alternative to conventional cement-based concrete.

d) The optimal replacement levels of fly ash observed in this study contribute to reducing cement usage without compromising mechanical performance, thus promoting environmentally responsible construction practices.

5.3 Scope for Future Work

a) The replacement level of fly ash can be extended beyond the current limits (e.g., up to 25% or 30%) to further evaluate its potential in sustainable concrete production.

b) Long-term performance studies, including durability tests such as resistance to sulfate attack, chloride penetration, and drying shrinkage, should be undertaken.

c) Repeated load and fatigue testing on beam specimens should be conducted to assess the suitability of fly ash concrete under real-life pavement loading conditions.

d) Life-cycle cost analysis and carbon footprint studies should be performed to quantify the environmental and economic benefits of using fly ash in Pavement Quality Concrete.

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