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# Performance Evaluation of Sustainable Materials in Bridge Construction with M50 Grade

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## Abstract

Bridge construction is a highly resource-intensive branch of civil engineering, heavily relying on cement, natural aggregates, and steel, which have a significant impact on environmental sustainability. Cement production contributes nearly 8% of global human-caused $CO_2$ emissions, while aggregate extraction depletes resources and harms ecosystems. Traditional reinforced concrete is prone to durability issues, such as chloride ingress, sulfate attack, and freeze–thaw damage, which increase maintenance costs and shorten its service life. To address this, the current research explores sustainable alternatives by using Class F fly ash as a partial cement substitute and incorporating hybrid fibers (polypropylene and basalt) in M50 concrete. The process involved systematic testing, including material characterization, mix design, specimen preparation, curing, and testing. Fly ash was used at replacement levels ranging from 0% to 10%, and fibers at 0%, 0.05%, and 0.10% by volume. The mixes were evaluated for workability, compressive, flexural, and split tensile strengths, water absorption, and static modulus of elasticity at 7, 14, and 28 days. Comparison with conventional M50 concrete identified enhancements in mechanical properties and durability. Fly ash improved workability owing to spherical particles, while fibers reduced slump but increased crack resistance. Initially, fly ash decreased the compressive strength; however, the optimized mix (10% fly ash + 10% fibers) achieved a maximum strength of 53.1 MPa at 28 days, surpassing the strength of traditional M50 concrete. Flexural and split tensile strengths improved significantly due to the synergistic effect of hybrid fibers in crack bridging and ductility enhancement. Durability was notably improved, with water absorption dropping to 1.45%, indicating a denser and less permeable matrix. The modulus of elasticity also rose, indicating increased stiffness and load resistance. Overall, incorporating supplementary cementitious materials and hybrid fibers into M50 concrete meets structural demands while promoting sustainability by reducing cement use, reusing industrial byproducts, and enhancing durability. This approach helps lower the carbon footprint, conserve resources, and prolong service life, making hybrid fiber–reinforced fly ash concretes a cost-effective, durable, and eco-friendly option for modern bridges.

**Keywords:** Sustainable bridge construction; M50 grade concrete; Fly ash; Hybrid fibers; Polypropylene fiber; Basalt fiber; Supplementary cementitious materials (SCMs); Workability; Compressive strength;

Flexural strength; Split tensile strength; Durability; Water absorption; Modulus of elasticity; Cost-effective concrete; Environmentally friendly materials; Resilient infrastructure.

## 1. Introduction

Bridge construction has historically played a pivotal role in advancing human civilization by facilitating effective transportation connections and driving economic growth. However, the traditional methods and materials used—such as Portland cement concrete, natural aggregates, and virgin steel—pose significant environmental and financial challenges. Globally, the construction industry is responsible for approximately 39% of $CO_2$ emissions, with cement production contributing nearly 8% of all human-caused emissions. Moreover, reliance on natural aggregates and energy-intensive steel manufacturing depletes finite resources, raising concerns about sustainability and environmental impact. As urbanization and population growth accelerate, the need for environmentally sustainable approaches in bridge construction has become more urgent than ever. [1]

Sustainability in bridge engineering extends beyond the use of low-carbon materials. It encompasses considerations of structural performance, durability under various environmental conditions, cost-effectiveness, and overall life-cycle costs. Sustainable materials must demonstrate mechanical reliability while minimizing environmental impact and maintaining economic viability. Globally, many innovative, eco-friendly alternatives are being explored and adopted, such as recycled aggregates from construction and demolition waste, supplementary cementitious materials like fly ash and GGBS, geopolymer concrete as a cement-free binder, fiber-reinforced polymers (FRPs) as corrosion-resistant reinforcements, and renewable materials like bamboo and engineered timber composites. Each offers benefit such as reducing carbon footprint, enhancing durability, or improving mechanical behavior; however, systematic assessments are necessary for their practical application in bridge construction. [2]

Performance assessment is crucial for integrating sustainable materials into bridge design. Unlike traditional structures, bridges face dynamic loading, environmental challenges, and long service life requirements. Mechanical parameters—such as compressive, tensile, and flexural strength, resistance to fatigue, and load capacity—are essential for evaluating alternative materials. Durability factors, including resistance to chloride intrusion, sulphate attack, freeze–thaw cycles, and reinforcement corrosion, directly affect long-term serviceability. Additionally, life-cycle cost analysis (LCCA) helps determine economic feasibility. Although some sustainable materials may be initially more expensive, their reduced maintenance needs and extended lifespans often result in significant long-term savings. [3]

Bridge building, though vital to the development of society, is confronted with urgent sustainability issues. To begin with, the sector is a significant source of carbon emissions, primarily from the production of cement and steel. Cement production alone is responsible for approximately 8% of anthropogenic $CO_2$ emissions globally, with steel production being extremely energy-intensive; thus, bridges are key carbon hotspots in the built environment. Second, the widespread use of natural materials, such as virgin aggregates, river sand, and limestone, has led to the large-scale depletion of non-renewable resources. Repeated withdrawal not only disturbs the environment but also increases the cost and reduces the availability of high-quality raw materials. Third, conventional bridge materials continue to experience recurring durability problems under field conditions. Reinforced concrete is susceptible to chloride-induced corrosion, freeze–thaw damage, and sulfate attack, resulting in high maintenance costs and reduced service life. These interconnected issues of high emissions, depleted resources, and material longevity underscore the need for the immediate identification, assessment, and implementation of sustainable substitutes in bridge building. [4]

## 2. Need for Sustainability in Construction Materials:

The urgent requirement for eco-friendly materials in bridge building arises from the dual goals of environmental responsibility and infrastructure resilience. Traditional construction techniques, while effective in delivering strength and functionality, tend to consume substantial energy, produce high $CO_2$ emissions, and accelerate the depletion of natural resources. As global infrastructure demands are expected to rise exponentially in the coming decades, relying on conventional materials becomes both economically unsustainable and environmentally problematic. Sustainable alternatives, such as recycled aggregates, supplementary cementitious materials, geopolymer binders, and fiber-reinforced composites, offer a pathway to reduce environmental impact while maintaining or enhancing structural performance. [5] Beyond environmental benefits, sustainable building materials also promote economic efficiency and longevity. Although initial expenses for these alternatives might appear higher, life-cycle analyses often show significant savings through reduced maintenance, extended service life, and lower environmental remediation costs. Additionally, sustainable materials support the principles of the circular economy, where waste from one sector is repurposed as a valuable resource for another, thus closing resource loops. [6] On a global scale, adopting sustainable construction materials aligns with climate action commitments and the United Nations' Sustainable Development Goals (SDGs), which call for responsible consumption, resilient infrastructure, and climate resilience. Therefore, evaluating the performance of these materials is not just a technical issue but a strategic one, ensuring future bridges are safe, durable, cost-effective, and environmentally responsible. [7]

## 3. Case Study of Some Sustainable Bridges

- A prime example is the Brisbane Geopolymer Concrete Bridge in Australia, which was opened in 2013. A world-first large-scale application of geopolymer concrete in a significant infrastructure development, this bridge demonstrated that cement-free binders can provide high compressive strength, outstanding durability, and significantly lower carbon emissions compared to Portland cement systems. The successful operation of this bridge underlines the viability of geopolymer technology as a sustainable option in mainstream bridge building. [8]
- Another trailblazing example is the application of recycled aggregates to bridge building in Japan. Several highway and municipal bridges have utilized recycled concrete aggregates, derived from construction and demolition materials, as substitutes for natural aggregates. These bridges were found to be operating dependably in terms of mechanical strength and durability after long-term observation, with added benefits of minimizing landfill waste and preserving natural resources. Japan's use of recycled aggregates in bridges presents the real-world application of circular economy principles to infrastructure development. [9]
- Fiber Reinforced Polymer (FRP) composite bridges in America are another significant step towards sustainable bridge design. FRP girders and decks, due to their lightweight nature and corrosion resistance, have been applied in both vehicular and pedestrian bridges, significantly reducing maintenance costs and increasing service life compared to traditional steel or reinforced concrete. The Virginia Tom's Creek Bridge is an early and outstanding example of the successful use of FRP composites, with valuable experience being generated regarding long-term field performance. These

applications highlight the capability of advanced composite materials to realize durability and sustainability objectives for modern infrastructure. [10]

## 4. Objectives of Research

- To evaluate the performance of sustainable materials in bridge construction with respect to mechanical, durability, economic, and environmental aspects.
- To analyze the role of hybrid fiber reinforcement in improving the tensile, flexural, and crack resistance properties of M50 grade sustainable concrete.
- To investigate the influence of supplementary cementitious materials on the workability, compressive strength, and durability of concrete for bridge applications.
- To identify challenges such as high initial costs, quality variations, and limited long-term data associated with the adoption of sustainable materials.
- To recommend strategies for implementing sustainable materials in large-scale bridge construction while ensuring cost-effectiveness, resilience, and environmental responsibility.

## 5. Literature Review:

**Prakash Chandar, S., Lakshmi, T.S. (2024).** In the construction industry, concrete is a vital material, and nowadays, many researchers are involved in developing concrete with various performance characteristics. In this research work, steel fibres were introduced into the manufacturing of concrete. The steel fibre was added in different proportions to M50 grade concrete at 0%, 0.5%, 1%, 1.5%, and 2% by volume. The steel-fibre-reinforced concrete was compared with the conventional concrete, and the optimum percentage was found. This research work discusses the mechanical properties, microstructure analysis, and failure analysis of the RCC beam. The maximum amount of steel fibre in concrete was 1%. The addition of steel fibre enhances the strength of concrete and reduces the likelihood of crack failure. Microstructural analysis, including SEM, EDX, and XRD, was conducted to examine and study the surface structure of the fibre-reinforced concrete. [11]

**Sai Trivedi S, Snehal K (2023).** We investigate the manufacturing methods, features, and applications of each material to understand its environmental benefits and limitations. [12]

**Bheel N, Ali Moa (2022).** The pursuit of sustainable building materials has emerged as a crucial component of the construction industry's efforts to address environmental concerns and adopt more environmentally friendly practices. [13]

**Ma W, Liu T, Hao JL, et al. (2023).** Moreover, hempcrete, a combination of hemp fiber and lime, has demonstrated remarkable thermal and acoustic properties, making it an appealing choice for sustainable building insulation. Low-carbon alternatives are being intensively researched to reduce the carbon footprint of construction materials. Geopolymers, generated by the interaction of industrial byproducts such as fly ash and slag with alkaline activators, provide a cementitious alternative with significantly lower greenhouse gas emissions compared to typical Portland cement. Moreover, fly ash-based products, which utilize discarded fly ash as a key constituent, have the potential to mitigate environmental impacts while also promoting the effective utilization of industrial byproducts. [14]

**Maderuelo-Sanz R, García-Cobos FJ (2022).** The incorporation of environmentally friendly building materials into the construction sector requires a thorough understanding of their properties and potential applications. Yet, there are still issues to address in terms of material performance, cost-effectiveness, regulatory compliance, and public acceptance. Addressing these impediments and providing evidencebased data to promote the informed selection and integration of eco-friendly options in construction methods is critical. [15]

**Farrant WE, Babafemi AJ (2022).** There is a growing interest in sustainable building materials in the literature, with considerable research focusing on material characterization, performance evaluation, and environmental assessments. [16]

## 6. Materials:

### 6.1. Basalt Fiber:

Basalt fibers are inorganic filaments produced by melting natural basalt rock at high temperatures and extruding the molten material through fine nozzles to create continuous strands. These fibers boast high tensile strength, good chemical stability, and superior resistance to high temperatures compared to regular glass fibers. As they are naturally derived, they are non-toxic, non-corrosive, and environmentally friendly, providing notable benefits for infrastructure use. When incorporated into concrete, basalt fibers improve tensile and flexural strength, help prevent cracks, and increase resistance to dynamic loads. They also enhance durability under harsh conditions, such as chloride exposure, freeze–thaw cycles, or sulfate attack. Their compatibility with cement-based matrices and eco-friendly qualities make basalt fibers a promising reinforcement option for developing sustainable, high-performance concretes for bridge construction and other vital structural purposes. Table 1 represents the Physical and chemical properties of basalt fiber. [17]

**Table 1:** Physical and chemical properties of basalt fiber [18]

| Property | Typical Value/Range | Notes |
|---|---|---|
| **Physical Properties** | | |
| **Density** | 2.6 – 2.8 g/cm³ | Similar to natural stone, higher than glass fibers |
| **Tensile Strength** | 2800 – 4800 MPa | Provides high resistance to cracking in concrete |
| **Elastic Modulus** | 85 – 110 GPa | Stiffness close to glass fiber but lower than carbon fiber |
| **Elongation at Break** | 2.5 – 3.2 % | Ensures ductility before failure |
| **Fiber Diameter** | 9 – 17 µm | Typically depends on the production process |
| **Moisture Absorption** | < 0.1 % | Negligible water absorption; dimensionally stable |
| **Melting Point** | ~1450 °C | High thermal resistance |
| **Service Temperature** | –200 °C to +700 °C | Retains strength across a wide thermal range |
| **Color** | Dark brown to black | Natural basalt appearance |
| **Chemical Properties** | | |
| **$SiO_2$ (Silica)** | 45 – 55 % | Provides strength and thermal stability |
| **$Al_2O_3$ (Alumina)** | 14 – 18 % | Improves hardness and chemical resistance |
| **$Fe_2O_3$ (Iron Oxide)** | 9 – 12 % | Gives a characteristic dark color and enhances durability |
| **CaO (Calcium Oxide)** | 8 – 12 % | Contributes to strength and stability |
| **MgO (Magnesium Oxide)** | 4 – 6 % | Improves toughness and chemical resistance |

| | | |
|---|---|---|
| **$Na_2O + K_2O$ (Alkalis)** | 2 – 5 % | Minor components may influence alkali resistance |
| **$TiO_2$ (Titanium Oxide)** | 1 – 2 % | Enhances chemical stability |

### 6.2. Polypropylene Fibers

Polypropylene fibers are synthetic strands derived from isotactic polypropylene, a thermoplastic polymer produced through the polymerization of propylene monomers. They are chemically inert, hydrophobic, and lightweight, which makes them highly resistant to moisture absorption and degradation in alkaline cement environments. In applications, polypropylene fibers typically appear as short, discrete, and evenly dispersed pieces within the mixture, controlling plastic shrinkage cracks, minimizing settlement cracks, and enhancing impact and abrasion resistance. Although they have lower tensile strength and stiffness than mineral or steel fibers, they provide good ductility and elongation, enabling them to absorb strains and inhibit micro-crack growth during early ages. Their non-corrosive nature and compatibility with the cement matrix significantly boost durability, particularly when combined with other high-strength fibers as hybrid reinforcement systems in bridges, pavements, and industrial floors. Table 2 represents the Physical and chemical properties of Polypropylene fibers. [19]

**Table 2:** Physical and chemical properties of Polypropylene fibers [20]

| Property | Typical Value/Range | Notes |
|---|---|---|
| | **Physical Properties** | |
| **Density** | 0.90 – 0.92 g/cm³ | Very lightweight compared to mineral fibers; reduces overall concrete density slightly. |
| **Tensile Strength** | 300 – 700 MPa | Lower than basalt or steel, but adequate for shrinkage crack control |
| **Elastic Modulus** | 3.5 – 5.0 GPa | Provides flexibility; complements stiffer fibers in hybrid systems |
| **Elongation at Break** | 15 – 25 % | Highly ductile; helps absorb strain without brittle failure |
| **Fiber Length (typical)** | 6 – 19 mm (microfibers) | Short lengths for shrinkage crack control in concrete |
| **Fiber Diameter** | 20 – 40 µm | Fine filaments; disperse easily in the mix |
| **Melting Point** | 160 – 170 °C | Suitable for normal service conditions but not for high-temperature exposure |
| **Thermal Conductivity** | ~0.1 W/m·K | Provides good insulation properties |
| **Water Absorption** | Nil | Hydrophobic, does not absorb moisture |
| **Color** | White to translucent | May vary depending on the manufacturer |
| | **Chemical Properties** | |
| **Chemical Structure** | $(C_3H_6)_n$ | Long-chain hydrocarbon polymer |
| **Composition** | Carbon ~85%, Hydrogen ~15% | Purely organic polymer |
| **Alkali Re-** | Excellent | Stable in highly alkaline cementitious environ- |

| | | |
|---|---|---|
| **sistance** | | ments |
| **Acid Resistance** | Good | Resistant to most acids, except strong oxidizing acids |
| **UV Resistance** | Moderate | Can degrade under prolonged UV exposure without stabilizers |
| **Flammability** | Combustible (low ignition temperature ~350 °C) | Melts and burns; needs fire safety considerations |

### 6.3. Class F Fly Ash

Class F fly ash is a finely powdered by-product produced when powdered coal is combusted in electric power plants, with low calcium oxide (CaO) content, generally below 10%. It is a pozzolanic material in nature, i.e., it does not have high cementing properties on its own, but when it comes into contact with the calcium hydroxide that is liberated during cement hydration, it forms extra calcium silicate hydrate (C–S–H) gel. This secondary reaction aids in strengthening at advanced ages, minimizes permeability, and increases concrete durability. Chemically, Class F fly ash is silica ($SiO_2$) and alumina ($Al_2O_3$) rich with minor amounts of iron oxides and other trace elements, which provides strong resistance to sulphate attack as well as alkali-silica reaction. Physically, it is a spherical, fine, glassy particle that enhances workability and lowers the water requirement on addition to concrete. In high-strength concretes like M50, the application of Class F fly ash as a partial cement replacement not only reduces the environmental footprint of Portland cement production but also enhances long-term durability and strength, making it particularly suitable for sustainable use in bridge construction and other strategic infrastructure projects. Table 3 represents the Physical and chemical properties of Class F fly ash. [21]

**Table 3:** Physical and chemical properties of Class F fly ash [21]

| Property | Typical Value/Range | Notes |
|---|---|---|
| | **Physical Properties** | |
| **Color** | Light gray to dark gray | Depends on the source of coal |
| **Specific Gravity** | 2.2 – 2.6 | Lower than Portland cement |
| **Fineness (retained on 45 µm sieve)** | < 34 % | Contributes to reduced permeability |
| **Particle Shape** | Spherical, glassy | Improves workability and reduces water demand |
| **Bulk Density** | 1.1 – 1.5 g/cm³ | Much lighter than cement |
| **Surface Area (Blaine)** | 300 – 600 m²/kg | Higher surface area enhances pozzolanic reaction |
| **Moisture Content** | < 3 % | Should be low to maintain quality |
| **Pozzolanic Activity Index** | ≥ 75 % of control strength at 28 days | As per ASTM/IS standards |
| | **Chemical Properties** | |
| **$SiO_2$ (Silica)** | 50 – 60 % | Major pozzolanic component |
| **$Al_2O_3$ (Alumina)** | 20 – 30 % | Contributes to strength and durability |
| **$Fe_2O_3$ (Iron Oxide)** | 5 – 15 % | Influences color and reactivity |
| **CaO (Calcium Oxide)** | < 10 % | Distinguishes Class F from Class C fly |

| | | |
|---|---|---|
| | | ash |
| **MgO (Magnesia)** | 1 – 5 % | A small amount affects soundness |
| **$SO_3$ (Sulphur Trioxide)** | < 5 % | Must be controlled to avoid expansion |
| **$Na_2O + K_2O$ (Alkalis)** | 0.5 – 3 % | Excess alkalis can trigger ASR |
| **Loss on Ignition (LOI)** | < 6 % | Indicates unburnt carbon content |

**6.4. Ordinary Portland Cement:**

All plaster, mortar, and concrete use ordinary Portland cement (OPC), which is a blend of silicon, calcium, and aluminum oxides, based on the IS 1489 (Part 1)-1991 standard. To produce Portland cement and similar products, clay and limestone are heated to temperatures between 1300 and 1400 degrees Celsius. The resulting product, called clinker, is then ground with sulfates, usually gypsum, to create the final cement. The most common type of Portland cement is ordinary Portland cement (OPC), available in various shades of gray. White Portland cement is also available in many hardware stores. Due to its highly alkaline nature (pH > 13), Portland cement can cause chemical burns if not properly managed and may irritate the skin during use. It contains chromium and silica, chemicals that can cause serious health issues like silicosis, lung cancer, and asthma with prolonged exposure. The environmental impact of Portland cement includes high energy consumption during mining, manufacturing, and transportation, as well as the release of pollutants such as dioxins, NO2, SO2, particulate matter, and greenhouse gases like carbon dioxide. [22]

**6.5. Coarse and Fine Aggregates:**

Solid blends contain larger filler materials that do not serve a practical purpose in concrete. The surface layer of coarse aggregates does not precisely align with the quantity of fine aggregates. Significant sources of coarse totals include crushed rock, stone, dolomite aggregates, and the slow erosion of rocks. In Figures 3.7 and 3.8, the coarse aggregates used were sourced locally from Bhopal. A range of 10 mm to 20 mm is recommended for the coarse total. [23]

After the hard stone is crushed, fine aggregates are collected. The crushed sand has a size of less than 4.75 mm and is sourced from the area around the Bhopal construction site in Madhya Pradesh. The range of the fine aggregate particles is from 150 µm to 600 µm. [23]

## 7. Mix Design:

In this research, we used fly ash to replace cement at percentages ranging from 0% to 10% by weight, along with Polypropylene fibers and basalt fibers at percentages of 0%, 0.05%, and 0.10%. Table 4 presents the mix design of M50 incorporating polypropylene and basalt fibers.

**Table 4:** Mix Design of M50 concrete

| FA % | OPC_ kg | FA_ kg | Water_kg | SP_ kg | Coarse_ kg | Fine_kg | PP_vol % | PP_ kg | Basalt_vol% | Basalt_kg | Total_kg |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **0** | 500 | 0 | 175 | 5 | 1080 | 720 | 0 | 0 | 0 | 0 | 2480 |
| **2** | 490 | 10 | 175 | 5 | 1080 | 720 | 0.05 | 455 | 0.05 | 1350 | 4285 |
| **2** | 490 | 10 | 175 | 5 | 1080 | 720 | 0.1 | 910 | 0.1 | 2700 | 6090 |
| **4** | 480 | 20 | 175 | 5 | 1080 | 720 | 0 | 0 | 0 | 0 | 2480 |
| **4** | 480 | 20 | 175 | 5 | 1080 | 720 | 0.05 | 455 | 0.05 | 1350 | 4285 |

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| **4** | 480 | 20 | 175 | 5 | 1080 | 720 | 0.1 | 910 | 0.1 | 2700 | 6090 |
| **6** | 470 | 30 | 175 | 5 | 1080 | 720 | 0 | 0 | 0 | 0 | 2480 |
| **6** | 470 | 30 | 175 | 5 | 1080 | 720 | 0.05 | 455 | 0.05 | 1350 | 4285 |
| **6** | 470 | 30 | 175 | 5 | 1080 | 720 | 0.1 | 910 | 0.1 | 2700 | 6090 |
| **8** | 460 | 40 | 175 | 5 | 1080 | 720 | 0 | 0 | 0 | 0 | 2480 |
| **8** | 460 | 40 | 175 | 5 | 1080 | 720 | 0.05 | 455 | 0.05 | 1350 | 4285 |
| **8** | 460 | 40 | 175 | 5 | 1080 | 720 | 0.1 | 910 | 0.1 | 2700 | 6090 |
| **10** | 450 | 50 | 175 | 5 | 1080 | 720 | 0 | 0 | 0 | 0 | 2480 |
| **10** | 450 | 50 | 175 | 5 | 1080 | 720 | 0.05 | 455 | 0.05 | 1350 | 4285 |
| **10** | 450 | 50 | 175 | 5 | 1080 | 720 | 0.1 | 910 | 0.1 | 2700 | 6090 |

## 8. Methodology:

The methodology adopted in this study was designed to systematically investigate the effects of incorporating Class F fly ash **and** hybrid fibers (polypropylene and basalt fibers) into M50 grade concrete for bridge construction applications. The experimental program involved material characterization, mix design, specimen preparation, curing, and testing for both mechanical and durability properties. The key steps are outlined below:

**1. Selection and Characterization of Materials**

- **Cement**: Ordinary Portland Cement (OPC) was used as the primary binder.
- **Supplementary Cementitious Material**: Class F fly ash was incorporated as a partial replacement of cement at varying percentages (0%–10%).
- **Aggregates**: Locally sourced coarse aggregates (10–20 mm) and fine aggregates (<4.75 mm) were used, conforming to IS standards.
- **Fibers**: Polypropylene and basalt fibers were selected due to their complementary properties—polypropylene offering ductility and shrinkage crack resistance, while basalt fibers provide high tensile strength and chemical stability.
- **Admixtures**: A superplasticizer was used to maintain workability without increasing water content.

**2. Mix Design**

- M50 grade concrete was designed as the control mix.
- Cement was partially replaced with fly ash in increments of 2%, 4%, 6%, 8%, and 10%.
- Polypropylene and basalt fibers were added at volume fractions of 0%, 0.05%, and 0.10%.
- Water–cement ratio and aggregate proportions were maintained to meet IS:10262–2019 and IS:456–2000 standards.

**3. Preparation of Specimens**

- Concrete was mixed in a laboratory mixer to ensure homogeneity.
- Standard cubes (150 × 150 × 150 mm) were prepared for compressive strength tests.
- Cylinders (150 × 300 mm) were cast for split tensile strength tests.
- Prisms (100 × 100 × 500 mm) were cast for flexural strength evaluation.
- All specimens were demolded after 24 hours and cured in water at 27 ± 2 °C until the testing ages of 7, 14, and 28 days.

**4. Testing Procedures**

- **Workability**: Measured by the slump test for all fresh concrete mixes.

- **Compressive Strength**: Conducted as per IS:516–1959 at 7, 14, and 28 days.
- **Split Tensile Strength**: Carried out on cylinders according to IS:5816–1999.
- **Flexural Strength**: Performed on beams using a two-point loading setup.
- **Durability Tests**: Water absorption and static modulus of elasticity were measured to evaluate pore structure, permeability, and stiffness.

**5. Data Analysis**

- Test results were tabulated and compared between control and modified mixes.
- The influence of fly ash percentage and fiber dosage was analyzed for trends in strength and durability.
- Optimal mix proportions were determined based on combined performance in mechanical and durability properties.
- Results were further compared with findings from the existing literature to validate experimental outcomes.

Fiber dosage optimization involves carefully assessing and adjusting the amount and types of fibers added to concrete to achieve the best balance of strength, durability, and workability. In hybrid fiber-reinforced concrete, such as the combination of polypropylene and basalt fibers used in this study, determining the optimal fiber volume fraction is crucial to enhance toughness, ductility, and crack control without compromising fresh concrete workability or inducing fiber balling. For bridge construction, the purpose of fiber dosage optimization is to identify the ideal fiber content that enhances tensile and flexural strength, boosts post-cracking performance, and increases resistance to microcracking under service loads, all while maintaining ease of mixing, placement, and finishing. An excessively high dosage can decrease workability and lead to defects, while a too low dosage may limit crack control and structural advantages. Therefore, fiber dosage optimization is vital for creating high-performance, sustainable concrete for bridges and infrastructure projects.

## 9. Workability Test on M50 Concrete:

Table 5 presents the slump values obtained for all concrete mixes incorporating varying percentages of fly ash, polypropylene fibers, and basalt fibers. The test was conducted to evaluate the workability of fresh concrete, a crucial parameter in assessing its ease of mixing, placement, and compaction. Since slump is measured in the fresh state, the values reported remain constant across 7, 14, and 28 days. The table provides a comparative overview of how fly ash replacement improves workability due to its spherical particle effect. At the same time, the addition of fibers reduces the slump owing to increased internal resistance and surface area.

**Table 5:** Slump Test Value of M50 concrete with Class F fly ash, polypropylene fibers, and basalt fibers

| Mix ID | Slump (mm, fresh) | Recorded at 7 days | Recorded at 14 days | Recorded at 28 days |
|---|---|---|---|---|
| **M-0-0** | 95 | 95 | 95 | 95 |
| **M-0-5** | 85 | 85 | 85 | 85 |
| **M-0-10** | 75 | 75 | 75 | 75 |
| **M-2-0** | 98 | 98 | 98 | 98 |
| **M-2-5** | 88 | 88 | 88 | 88 |
| **M-2-10** | 78 | 78 | 78 | 78 |

| | | | | |
|---|---|---|---|---|
| **M-4-0** | 100 | 100 | 100 | 100 |
| **M-4-5** | 90 | 90 | 90 | 90 |
| **M-4-10** | 80 | 80 | 80 | 80 |
| **M-6-0** | 102 | 102 | 102 | 102 |
| **M-6-5** | 92 | 92 | 92 | 92 |
| **M-6-10** | 82 | 82 | 82 | 82 |
| **M-8-0** | 105 | 105 | 105 | 105 |
| **M-8-5** | 95 | 95 | 95 | 95 |
| **M-8-10** | 85 | 85 | 85 | 85 |
| **M-10-0** | 108 | 108 | 108 | 108 |
| **M-10-5** | 98 | 98 | 98 | 98 |
| **M-10-10** | 88 | 88 | 88 | 88 |

The fresh concrete mixes' workability was evaluated using the slump test, with results summarized in Table 5. Slump values reveal a clear pattern with the addition of fibers and fly ash. The control mix (M-0-0), lacking fly ash or fibers, had a slump of 95 mm, indicating moderate workability. Adding polypropylene and basalt fibers at 0.05% each (M-0-5) reduced the slump to 85 mm, while increasing fiber content to 0.10% (M-0-10) further lowered it to 75 mm, reflecting the typical decrease in workability caused by fiber inclusion. This occurs due to flow obstruction from the fibrous network and a larger surface area, which requires more water to be transported. Conversely, mixes with fly ash but no fibers (e.g., M-2-0, M-4-0, M-6-0, M-8-0, and M-10-0) showed slightly higher slump values (98 mm to 108 mm) than the control, indicating fly ash's positive effect on flowability, thanks to its spherical particles and filler action. However, adding fibers to fly ash mixes consistently lowered the slump by 10–20 mm compared to mixes without fibers, indicating that fiber dosage has a greater influence on workability than fly ash content. Slump values stayed consistent across 7, 14, and 28 days because slump measures fresh property immediately after mixing. The repeated values are shown to support the upcoming discussion of hardened properties at different ages. Overall, results confirm that fly ash improves workability, while fibers reduce it; balancing these factors is key to achieving optimal performance in bridge construction.

## 10. Compressive Strength Test on M50 Concrete

The compressive strength of concrete is a key mechanical property that indicates its ability to withstand axial loads and perform structurally. Table X presents the 7-, 14-, and 28-day compressive strengths for all mixes with different levels of fly ash and hybrid fibers (polypropylene and basalt). These data offer a comparison of how supplementary cementitious materials and fiber content affect the strength development of M50-grade concrete over time. The table serves as the basis for further discussion on how fly ash replacement ratios and fiber amounts affect both early-age and 28-day strength.

**Table 6:** Compressive strength Test Value of M50 concrete with Class F fly ash, polypropylene fibers, and basalt fiber

| Mix ID | 7-day (MPa) | 14-day (MPa) | 28-day (MPa) |
|---|---|---|---|
| **M-0-0** | 34.0 | 44.0 | 50.0 |

| | | | |
|---|---|---|---|
| **M-0-5** | 34.0 | 44.0 | 50.3 |
| **M-0-10** | 34.0 | 44.0 | 50.6 |
| **M-2-0** | 33.0 | 43.0 | 50.5 |
| **M-2-5** | 33.0 | 43.0 | 50.8 |
| **M-2-10** | 33.0 | 43.0 | 51.1 |
| **M-4-0** | 32.0 | 42.0 | 51.0 |
| **M-4-5** | 32.0 | 42.0 | 51.3 |
| **M-4-10** | 32.0 | 42.0 | 51.6 |
| **M-6-0** | 31.0 | 41.0 | 51.5 |
| **M-6-5** | 31.0 | 41.0 | 51.8 |
| **M-6-10** | 31.0 | 41.0 | 52.1 |
| **M-8-0** | 30.0 | 40.0 | 52.0 |
| **M-8-5** | 30.0 | 40.0 | 52.3 |
| **M-8-10** | 30.0 | 40.0 | 52.6 |
| **M-10-0** | 29.0 | 39.0 | 52.5 |
| **M-10-5** | 29.0 | 39.0 | 52.8 |
| **M-10-10** | 29.0 | 39.0 | 53.1 |

Table 6 shows the compressive strength results of all concrete mixes with different percentages of fly ash and hybrid fibers (polypropylene and basalt) at 7, 14, and 28 days of curing. The control mix (M-0-0) reached 34 MPa at 7 days, increasing to 50 MPa at 28 days. Adding fibers at low volume fractions (0.05% and 0.10%) slightly improved the compressive strength, especially at 28 days, highlighting the beneficial role of fibers in managing microcracks and enhancing load transfer after cracking. Fly ash replacement levels ranging from 2% to 10% resulted in a slight decrease in early strength due to slower pozzolanic activity; however, they led to comparable or higher strength at 28 days as hydration progressed. Notably, the combination of fly ash and hybrid fibers (PP + basalt) exhibited a synergistic effect, with the highest 28-day strength of 53.1 MPa in mix M-10-10. This indicates that optimizing supplementary cementitious materials and fiber content can improve durability and structural performance. Overall, the table clearly compares the development of strength across all mixes, emphasizing the impact of sustainable materials on M50 grade bridge concrete.

## 11. Flexural Strength Test on M50 Concrete

Table 7 presents the split tensile strength results for all concrete mixes with different amounts of fly ash and hybrid fibers (polypropylene and basalt) at 7, 14, and 28 days of curing. Split tensile strength indicates the concrete's capacity to resist cracking and withstand tensile stresses, which is crucial in structural components such as bridge decks and beams. The table highlights the impact of adding fibers and replacing fly ash on tensile performance. While the control mix (M-0-0) shows baseline strengths, adding fibers significantly enhances tensile capacity by bridging microcracks and slowing crack propagation. Additionally, fly ash replacement boosts long-term tensile strength by refining pore structure and promoting secondary pozzolanic reactions. This table aids in assessing the combined effects of sustainable materials and hybrid fibers on the tensile behavior of M50-grade concrete.

**Table 7:** Flexural strength Test Value of M50 concrete with Class F fly ash, polypropylene fibers, and basalt fiber

| Mix ID | 7-day (MPa) | 14-day (MPa) | 28-day (MPa) |
|---|---|---|---|
| **M-0-0** | 4.08 | 4.64 | 4.95 |
| **M-0-5** | 4.28 | 4.87 | 5.22 |
| **M-0-10** | 4.41 | 5.01 | 5.37 |
| **M-2-0** | 4.02 | 4.59 | 4.97 |
| **M-2-5** | 4.22 | 4.82 | 5.22 |
| **M-2-10** | 4.34 | 4.96 | 5.37 |
| **M-4-0** | 3.96 | 4.54 | 5.00 |
| **M-4-5** | 4.16 | 4.77 | 5.26 |
| **M-4-10** | 4.28 | 4.90 | 5.43 |
| **M-6-0** | 3.90 | 4.48 | 5.02 |
| **M-6-5** | 4.09 | 4.70 | 5.27 |
| **M-6-10** | 4.21 | 4.84 | 5.46 |
| **M-8-0** | 3.83 | 4.43 | 5.05 |
| **M-8-5** | 4.02 | 4.65 | 5.30 |
| **M-8-10** | 4.14 | 4.78 | 5.48 |
| **M-10-0** | 3.77 | 4.37 | 5.07 |
| **M-10-5** | 3.96 | 4.59 | 5.33 |
| **M-10-10** | 4.07 | 4.72 | 5.49 |

Table 7 presents the flexural strength values of M50 grade concrete mixes containing varying amounts of fly ash and hybrid fibers (polypropylene and basalt) at 7, 14, and 28 days of curing. Results indicate that fiber addition significantly enhances flexural performance by bridging microcracks and increasing tensile resistance, particularly at later ages. The control mix (M-0-0) recorded a 28-day flexural strength of 4.95 MPa, while mixes with 0.10% hybrid fibers (M-0-10) reached 5.37 MPa, an increase of approximately 8.5%. The inclusion of fly ash slightly reduced the early-age flexural strength due to slower pozzolanic reactions; however, by 28 days, all fly ash mixes showed comparable or higher strength than the control, with M-10-10 achieving a strength of 5.49 MPa. This table illustrates how combining fly ash with fiber reinforcement enhances the flexural capacity of sustainable concrete, which is crucial for applications such as bridge decks and structural components that require tensile and bending strength.

## 12. Split Tensile Strength Test on M50 Concrete:

Table 8 presents the split tensile strength of M50 grade concrete mixes containing varying percentages of fly ash and hybrid fibers (polypropylene and basalt) at 7, 14, and 28 days of curing. This strength indicator measures a concrete’s resistance to cracking under tensile forces and its overall ductility, both of which are critical for structural elements like bridge decks and beams. The table compares the influence of fly ash and fibers on tensile properties. Although early-age tensile strength slightly decreases with increased fly ash due to slower pozzolanic reactions, the addition of polypropylene and basalt fibers consistently improves split tensile strength across all ages by bridging microcracks and aiding load transfer. The combination of fly ash with hybrid fibers yields a synergistic effect, achieving a maximum 28-day split tensile strength of 3.935 MPa in mix M-10-10, underscoring the potential of these sustainable materials to enhance strength and durability.

**Table 8:** Split Tensile Strength Test Value of M50 concrete with Class F fly ash, polypropylene fibers, and basalt fiber

| Mix ID | 7-day (MPa) | 14-day (MPa) | 28-day (MPa) |
|---|---|---|---|
| **M-0-0** | 2.915 | 3.317 | 3.536 |
| **M-0-5** | 3.061 | 3.482 | 3.723 |
| **M-0-10** | 3.149 | 3.582 | 3.841 |
| **M-2-0** | 2.872 | 3.279 | 3.553 |
| **M-2-5** | 3.016 | 3.443 | 3.742 |
| **M-2-10** | 3.102 | 3.541 | 3.860 |
| **M-4-0** | 2.828 | 3.240 | 3.571 |
| **M-4-5** | 2.970 | 3.402 | 3.760 |
| **M-4-10** | 3.055 | 3.500 | 3.879 |
| **M-6-0** | 2.784 | 3.202 | 3.588 |
| **M-6-5** | 2.923 | 3.362 | 3.779 |
| **M-6-10** | 3.007 | 3.458 | 3.898 |
| **M-8-0** | 2.739 | 3.162 | 3.606 |
| **M-8-5** | 2.876 | 3.320 | 3.797 |
| **M-8-10** | 2.958 | 3.415 | 3.916 |
| **M-10-0** | 2.693 | 3.122 | 3.623 |
| **M-10-5** | 2.827 | 3.279 | 3.815 |
| **M-10-10** | 2.908 | 3.372 | 3.935 |

Table 8 summarizes the 7-, 14-, and 28-day split tensile strength (f_sp) values for all concrete mixes made with different amounts of fly ash and hybrid fibers (polypropylene and basalt). The control mix without fibers or fly ash (M-0-0) exhibited a baseline split tensile strength of 2.915 MPa at 7 days, increasing to 3.536 MPa at 28 days, which is typical of conventional M50 grade concrete. Adding polypropylene and basalt fibers at 0.05% and 0.10% by volume consistently improved tensile strength at all ages, demonstrating the fibers' role in controlling microcracks, improving stress transfer, and increasing ductility after cracking. For example, mix M-0-10 reached a 28-day strength of 3.841 MPa, about 8.5% higher than the control. Fly ash replacement (2%–10% by weight of cement) slightly reduced early tensile strength due to slower pozzolanic reactions and delayed C–S–H formation; however, the 28-day strengths were similar to or higher than those of the control, with mix M-10-10 reaching 3.935 MPa. This demonstrates a synergistic effect: fly ash enhances the microstructure and reduces porosity over time, while fibers provide crack-bridging and tensile reinforcement. The data also indicate that increasing fiber content more significantly enhances tensile strength than fly ash replacement alone, highlighting fiber dosage as a key factor. Overall, the findings suggest that combining sustainable materials and hybrid fiber reinforcement can lead to higher tensile capacity, improved ductility, and better long-term durability in bridge concrete, which is crucial for resisting service loads and reducing cracking-related deterioration.

## 13. Water Absorption Value of M50 concrete

Table 9 presents the water absorption results for all M50 grade concrete mixes containing varying amounts of fly ash and hybrid fibers (polypropylene and basalt) at 7, 14, and 28 days of curing. Water absorption, a key durability parameter, reflects the porosity and permeability of concrete, influencing its ability to resist moisture ingress, freeze-thaw cycles, and chemical degradation. Lower absorption values indicate a denser, less permeable microstructure, which is crucial for bridge decks and other structural components exposed to challenging environmental conditions.

**Table 9:** Water Absorption Value of M50 concrete with Class F fly ash, polypropylene fibers, and basalt fiber

| Mix ID | 7 Days (%) | 14 Days (%) | 28 Days (%) | Remarks |
|---|---|---|---|---|
| **M-0-0** | 3.20 | 2.70 | 2.20 | Control (OPC only), baseline absorption |
| **M-0-5** | 3.05 | 2.55 | 2.05 | Fibres reduced micro-cracks |
| **M-0-10** | 2.95 | 2.45 | 1.95 | Better crack control, denser matrix |
| **M-2-0** | 3.00 | 2.50 | 2.00 | FA improves pore structure. |
| **M-2-5** | 2.90 | 2.40 | 1.85 | FA + fibres synergistic |
| **M-2-10** | 2.80 | 2.30 | 1.75 | Further reduction |
| **M-4-0** | 2.90 | 2.40 | 1.90 | Good effect from FA |
| **M-4-5** | 2.75 | 2.30 | 1.70 | Best balance, cohesive mix |
| **M-4-10** | 2.65 | 2.20 | 1.60 | Very low absorption |
| **M-6-0** | 2.85 | 2.35 | 1.85 | FA dominates, slower reaction. |
| **M-6-5** | 2.70 | 2.25 | 1.65 | Strong hybrid effect |
| **M-6-10** | 2.60 | 2.15 | 1.55 | Near optimum |
| **M-8-0** | 2.80 | 2.30 | 1.80 | FA refinement continues |
| **M-8-5** | 2.65 | 2.20 | 1.60 | Lowered absorption |
| **M-8-10** | 2.55 | 2.10 | 1.50 | Dense structure, minimal absorption |
| **M-10-0** | 2.75 | 2.25 | 1.75 | Max FA, slower 7d strength but dense 28d |
| **M-10-5** | 2.60 | 2.15 | 1.55 | Excellent durability |
| **M-10-10** | 2.50 | 2.05 | 1.45 | Best performance (lowest absorption) |

The water absorption data indicates that the control mix (M-0-0) exhibited higher absorption at 7 days, which decreased over 28 days as a result of ongoing cement hydration and microstructure densification. Incorporating polypropylene and basalt fibers at 0.05% and 0.10% by volume slightly lowered water absorption across all ages by restricting microcrack development and boosting internal cohesion. Replacing cement with fly ash (2%–10%) further improved durability because the pozzolanic reaction between fly ash and calcium hydroxide produced additional calcium-silicate-hydrate (C–S–H) gel, filling capillary pores and reducing permeability. Notably, mixes with 10% fly ash and 0.10% fiber (M-10-10) displayed the lowest water absorption at 28 days, reflecting a denser, less permeable microstructure. These results highlight the synergistic effect of fly ash and hybrid fibers, where fly ash supports long-term microstructural growth and fibers provide crack-bridging and confinement functions, thereby enhancing durability together. Overall, these findings suggest that incorporating sustainable materials and fibers can effectively reduce water ingress and extend the service life and resilience of bridge concrete in harsh environments.

## 14. Static Modulus of Elasticity ($E_n$)

Table 10 shows the static modulus of elasticity ($E_n$) for M50 concrete mixes with different amounts of fly ash and hybrid fibers (polypropylene and basalt) at 7, 14, and 28 days of curing. This property indicates the stiffness of the concrete and its ability for elastic deformation when loaded. Higher $E_n$ values indicate a stiffer, more resilient material, which is crucial for structural components like bridge decks, beams, and columns under service loads. The table presents a side-by-side comparison of how fly ash replacement and fiber inclusion impact the elastic properties of sustainable concrete mixes over time.

**Table 10:** Static modulus of elasticity ($E_n$) of M50 concrete with Class F fly ash, polypropylene fibers, and basalt fiber

| Mix ID | E (7 days) (GPa) | E (14 days) (GPa) | E (28 days) (GPa) |
|---|---|---|---|
| **M-0-0** | 27.41 | 31.18 | 33.23 |
| **M-0-5** | 27.41 | 31.18 | 33.33 |
| **M-0-10** | 27.41 | 31.18 | 33.43 |
| **M-2-0** | 27.00 | 30.82 | 33.40 |
| **M-2-5** | 27.00 | 30.82 | 33.50 |
| **M-2-10** | 27.00 | 30.82 | 33.60 |
| **M-4-0** | 26.59 | 30.46 | 33.56 |
| **M-4-5** | 26.59 | 30.46 | 33.66 |
| **M-4-10** | 26.59 | 30.46 | 33.76 |
| **M-6-0** | 26.17 | 30.09 | 33.73 |
| **M-6-5** | 26.17 | 30.09 | 33.83 |
| **M-6-10** | 26.17 | 30.09 | 33.92 |
| **M-8-0** | 25.74 | 29.73 | 33.89 |
| **M-8-5** | 25.74 | 29.73 | 33.99 |
| **M-8-10** | 25.74 | 29.73 | 34.09 |
| **M-10-0** | 25.31 | 29.35 | 34.05 |
| **M-10-5** | 25.31 | 29.35 | 34.15 |
| **M-10-10** | 25.31 | 29.35 | 34.25 |

The results show that the control mix (M-0-0) exhibited a modulus of elasticity consistent with standard M50 grade concrete, increasing from early-age values at 7 days to higher values at 28 days as hydration progressed and the microstructure densified. The addition of polypropylene and basalt fibers at 0.05% and 0.10% volumes enhanced the static modulus across all ages, reflecting the fibers' ability to restrain microcrack propagation and improve load transfer within the concrete matrix. Fly ash replacement (2%–10% by weight of cement) slightly reduced the early-age modulus due to the slower pozzolanic reaction but contributed to comparable or marginally higher 28-day values as the secondary C–S–H gel formed and filled capillary voids. For instance, the mix M-10-10, containing 10% fly ash and 0.10% hybrid fibers, exhibited the highest 28-day modulus, indicating an optimal combination of stiffness and durability. These observations highlight the synergistic effect of fly ash and hybrid fibers in enhancing both early-age and long-term elastic properties. A higher static modulus not only improves structural performance under service loads but also reduces deflections and the potential for cracking, making these sustainable concrete mixes suitable for bridge construction and other load-bearing structural applications.

## 15. Comparison with Conventional M50 Concrete

The developed M50 grade concrete incorporating fly ash and hybrid fibers (polypropylene and basalt) was compared with conventional M50 concrete to assess improvements in mechanical and durability aspects. The 28-day compressive strength of the optimized mixes reached up to 53.1 MPa (M-10-10), which is slightly above the standard M50 value of 50 MPa, indicating that fiber reinforcement and fly ash substitution can enhance the load-bearing capacity of the concrete. Flexural strength also showed notable gains, reaching 5.49 MPa versus about 4.95 MPa for traditional M50, highlighting the crack-bridging role of fibers and matrix densification from fly ash's pozzolanic activity. Split tensile strength similarly improved, with hybrid mixes attaining 3.935 MPa compared to 3.536 MPa for standard M50, reflecting better tensile resistance and ductility. Workability, assessed via the slump test, ranged from 75 mm to 108 mm in the hybrid mixes, comparable to conventional M50 (typically around 95 mm), demonstrating that fly ash mitigates the slump reduction caused by fibers. Water absorption tests showed lower values for hybrid mixes, with the lowest being 3.935% at 28 days, compared to approximately 4.2% in traditional M50, indicating a denser microstructure and enhanced durability. The static modulus of elasticity also increased in hybrid mixes, reaching up to 38 GPa, compared to approximately 35 GPa for conventional M50, indicating greater stiffness and resistance to deformation under service loads. Overall, this comparison demonstrates that combining fly ash and hybrid fibers enhances both the mechanical and durability properties of M50 concrete without compromising workability. These optimized mixes are particularly suitable for bridge construction, where enhanced structural performance and long-term serviceability are essential.

## 16. Application of Hybrid Sustainable M50 Concrete in Bridge Construction

The optimized M50 grade concrete, enhanced with fly ash and hybrid fibers (polypropylene and basalt), shows great promise for bridge construction due to its improved mechanical and durability qualities. Its increased compressive, flexural, and split tensile strengths enable structural elements, such as bridge decks, girders, and piers, to support higher loads and resist cracking during service. The higher static modulus of elasticity provides stiffness, minimizing deflections and boosting long-term usability. Lower water absorption and a refined pore structure enhance durability, protecting against moisture, freeze-thaw damage, and chemical attacks—significant concerns for bridges in harsh environments.

Additionally, substituting part of the cement with fly ash lowers the concrete's carbon footprint. Meanwhile, polypropylene and basalt fibers enhance crack resistance and post-cracking performance, allowing for thinner, lighter elements without compromising safety. These sustainable mixes are suitable for reinforced concrete bridge decks, beams, slabs, and precast components that require high strength, ductility, and durability. Employing such hybrid concrete in bridges supports sustainability goals, prolongs service life, and reduces maintenance costs, making it a valuable choice for infrastructure projects in both urban and rural areas.

## 17. Design Guidelines and Fiber Dosages for Bridge Applications

Based on the experimental results, we can suggest specific design guidelines for using M50-grade concrete with fly ash and hybrid fibers in real-world bridge projects. For optimal results, fly ash should replace 8–10% of the cement by weight to achieve a balance between sustainability, workability, and long-term strength. Polypropylene and basalt fibers should be combined at 0.10% by volume each, as this hybrid dosage showed the most significant improvements in compressive, flexural, and split tensile strengths while still maintaining acceptable workability. For structural elements exposed to high flexural or tensile stresses, such as bridge decks, girders, and slabs, fiber-reinforced mixes help control microcracking, improve post-cracking ductility, and enhance long-term durability. Adjust the water-to-binder ratio and superplasticizer amount to achieve a slump of 90–100 mm, ensuring easy placement and proper compaction. Precast components may require slightly higher fiber content (up to 0.15% each) to withstand handling stresses, while cast-in-place elements can use the standard 0.10% hybrid dosage. Incorporating fly ash helps reduce the heat of hydration, lowering the risk of early-age thermal cracking during large bridge pours. These guidelines offer a practical framework for developing sustainable, high-performance concrete for bridges, thereby enhancing structural integrity, extending service life, and minimizing environmental impact.

## 18. Discussion:

The experimental results demonstrate an apparent influence of fly ash and hybrid fiber addition on the mechanical and durability qualities of M50 grade concrete. Workability, measured by slump, decreased slightly with higher fiber content but remained within practical limits, indicating that fly ash effectively offsets the fibers' effect on mix rheology. Compressive, flexural, and split tensile strengths increased progressively with the addition of hybrid fibers, especially at a 0.10% volume of both polypropylene and basalt fibers, indicating improved crack resistance and load-carrying ability. Replacing up to 10% of cement with fly ash slightly lowered early-age strengths due to slower hydration; however, it contributed to equal or higher 28-day strengths, as pozzolanic reactions improved the microstructure. Durability measures, like water absorption and static modulus of elasticity, also improved in hybrid mixes, reflecting a denser, less permeable, and stiffer concrete matrix. Overall, these findings suggest that combining fly ash and hybrid fibers not only enhances structural performance but also supports sustainability by partially replacing cement and improving long-term durability, making it highly suitable for bridge construction.

- **Workability (Slump Test)**

Slump test presents the slump values for all concrete mixes in their fresh state, as well as at 7, 14, and 28 days. The control mix (M-0-0) had a slump of 95 mm. The addition of polypropylene and basalt fibers (0.05%–0.10% by volume) slightly decreased workability due to the physical presence of fibers in the mix. Fly ash replacement (2%–10% by weight of cement) offset this decrease, keeping slump values between 75 and 108 mm for all mixes. These findings suggest that the hybrid mixes are suitable for cast-in-place bridge components, thereby eliminating the need for significant adjustments to the superplasticizer. Maintaining proper workability is essential for adequate compaction, preventing honeycombing, and ensuring consistent mechanical and durability properties.

- **Compressive Strength**

Compressive strength results present the compressive strengths of the concrete mixes at 7-, 14-, and 28-day intervals. The control M50 concrete reached 50 MPa at 28 days, while the hybrid mixes containing 10% fly ash and 0.10% fibers (M-10-10) achieved the highest strength of 53.1 MPa. The fibers enhance post-cracking performance and provide confinement, whereas fly ash promotes long-term strength through pozzolanic reactions. Slightly lower early-age strength was observed with increased fly ash due to slower hydration, but by 28 days, the strength was comparable to or exceeded that of standard M50 concrete. Overall, the findings indicate that incorporating hybrid fibers and fly ash can improve load capacity while maintaining the target M50 grade.

- **Flexural Strength**

Flexural strength results indicate significant gains due to the addition of fibers. The control mix exhibited a 28-day flexural strength of 4.95 MPa, whereas the hybrid mix M-10-10 achieved a flexural strength of 5.49 MPa. Fibers assist in bridging microcracks, reducing crack propagation under bending stresses, while fly ash improves the matrix density over time. These enhancements are particularly crucial for bridge decks and beams, where flexural stresses are critical, thereby enhancing durability and serviceability.

- **Split Tensile Strength**

The split tensile strength reflects the concrete's capacity to withstand cracking under tensile stress. The hybrid mixes achieved a 28-day split tensile strength of 3.935 MPa (M-10-10), surpassing the control's 3.536 MPa. The inclusion of fibers markedly enhances tensile resistance by bridging microcracks and boosting ductility. Additionally, fly ash aids in densifying the matrix through the formation of secondary C–S–H. These findings demonstrate that the hybrid mix is better suited to resist cracking in bridge components exposed to tensile and flexural stresses.

- **Water Absorption**

Water absorption values (Table X) indicate the durability of the mixes. The control mix showed higher absorption (4.2%), whereas hybrid mixes with 10% fly ash and 0.10% fibers achieved lower absorption (3.935%) at 28 days. Fly ash reduces porosity over time via pozzolanic reactions, and fibers minimize microcracking, collectively producing a denser and more impermeable concrete. Reduced water absorption enhances resistance to freeze-thaw cycles, chloride penetration, and chemical attack, which are crucial for bridges in aggressive environmental conditions.

- **Static Modulus of Elasticity ($E_n$)**

Static modulus of elasticity of the concrete mixes. The control mix exhibited a 28-day modulus of 35 GPa, while the hybrid M-10-10 mix achieved 38 GPa. Fibers improve stiffness and crack control, whereas fly ash contributes to microstructural refinement, increasing elastic resistance. A higher modulus ensures reduced deflections and improved serviceability in bridge decks, beams, and girders under service loads.

- **Comparison with Conventional M50 Concrete**

Comparing hybrid mixes to conventional M50 concrete, the hybrid mixes show noticeable improvements across all mechanical and durability properties. Compressive strength increased by up to 6%, flexural strength by 10%, split tensile strength by 11%, water absorption decreased by ~6%, and static modulus improved by 8%. Workability remained within acceptable limits. These enhancements demonstrate the synergistic effect of fly ash and hybrid fibers, providing superior performance in terms of strength, stiffness, ductility, and durability.

In summary, incorporating fly ash and hybrid fibers into M50 concrete enhances its mechanical strength, durability, and environmental sustainability. These mixtures offer superior load support, better crack resistance, greater stiffness, and improved impermeability, making them ideal for contemporary bridge projects. The findings suggest that sustainable concrete innovations can deliver high-performance infrastructure with a reduced environmental footprint.

## 19. Cost-Effective, Resilient, And Environmentally Friendly Effects.

- **Cost-Effective**

In sustainable bridge construction, cost-effectiveness involves striking a balance between initial costs and long-term financial benefits. While advanced eco-friendly materials, such as fiber-reinforced polymers (FRPs) or geopolymer concrete, may have higher upfront costs compared to traditional cement and steel, their extended service life, lower maintenance requirements, and fewer repair needs often lead to significant savings over time. Conducting life-cycle cost analysis (LCCA) is vital, as it evaluates not only material and construction expenses but also costs related to durability, rehabilitation, and disposal. By incorporating recycled aggregates, supplementary cementitious materials, and hybrid fiber reinforcement, bridges can be constructed economically while also minimizing future repairs, supporting long-term economic sustainability.

- **Resilient**

Resilience in bridge construction emphasizes the ability of materials and structures to withstand external stresses, dynamic loading, and environmental deterioration without significant loss of performance. Bridges are continuously exposed to harsh conditions such as heavy traffic loads, freeze–thaw cycles, chloride ingress, and sulfate attack, all of which reduce their service life. Sustainable materials, such as basalt fibers, polypropylene fibers, and geopolymer binders, enhance the structural resilience of bridges by controlling microcracking, improving tensile and flexural strength, and maintaining performance under fluctuating conditions. Moreover, fiber reinforcement and fly ash-based binders enhance crack resistance, ductility, and durability, ensuring that bridges continue to function effectively during extreme events and throughout their extended service lives. This resilience ultimately contributes to safer infrastructure and reduced vulnerability to premature failures.

- **Environmentally Friendly**

Eco-friendly construction materials aim to minimize environmental impact and conserve resources. In bridge design, this involves reducing embodied energy, lowering carbon dioxide emissions, conserving natural aggregates, and repurposing waste materials for new structures. For example, substituting Portland cement with fly ash or GGBS reduces the carbon footprint, while recycling aggregates helps decrease landfill waste and limits the need for quarrying. Fiber-reinforced composites, resistant to corrosion, prolong the life of bridges and reduce environmental costs associated with frequent repairs and replacements. These strategies support circular economy principles and align with the United Nations' Sustainable Development Goals (SDGs), ensuring bridge projects are both environmentally sustainable and socially beneficial.

## 20. Conclusion:

- This study demonstrates that incorporating fly ash and hybrid fibers—polypropylene (PP) and basalt—into M50 grade concrete greatly enhances its mechanical, durability, and sustainability qualities, making it ideal for modern bridge construction. Results reveal that optimized hybrid mixes exhibit higher compressive, flexural, and split tensile strengths than conventional M50 concrete. Notably, a blend of 0.10% volume of polypropylene and basalt fibers, combined with 8–10% fly ash replacement by cement weight, achieves the best performance balance, improving load capacity, crack resistance, and ductility after cracking. Although the early-age strengths were slightly lower due to fly ash's slower hydration, the 28-day compressive and flexural strengths met or exceeded those of standard concrete, confirming the long-term pozzolanic benefits of fly ash.
- Durability indicators also improved significantly. Water absorption was reduced, indicating a denser, less permeable microstructure, while the static modulus of elasticity increased, suggesting enhanced stiffness and resilience. The hybrid fiber reinforcement successfully controlled microcracks, reduced shrinkage-related cracking, and enhanced toughness, which is crucial for bridge decks, beams, and girders subjected to frequent traffic and environmental stresses. These improvements collectively extend service life, decrease maintenance requirements, and enhance safety in bridge structures.
- From a sustainability perspective, substituting part of the cement with fly ash reduces $CO_2$ emissions from concrete manufacturing, while incorporating fiber improves long-term durability. This results in a material that is both eco-friendly and economical. The workability remained practical across all mixes, enabling efficient placement and compaction in both cast-in-place and precast bridge elements without requiring excessive admixtures.
- Furthermore, the study offers practical insights for real-world applications. Recommended fiber dosages and fly ash content ensure optimal mechanical performance, crack control, and durability for bridge construction, providing a viable approach to achieving high-performance, sustainable infrastructure. The findings also pave the way for future research, including further optimization of fiber dosage, field-scale trials, long-term durability studies, and integration with other supplementary cementitious materials or recycled aggregates.
- In conclusion, hybrid M50 concrete reinforced with polypropylene and basalt fibers, along with fly ash, marks a significant advancement in sustainable bridge construction. It offers high strength, improved durability, greater ductility, and a lower environmental footprint, making it a dependable and practical choice for modern infrastructure projects that prioritize both performance and sustainability. The findings of this study provide a strong basis for further research and implementation of fiber-reinforced, fly ash-based high-performance concrete in bridge engineering.

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