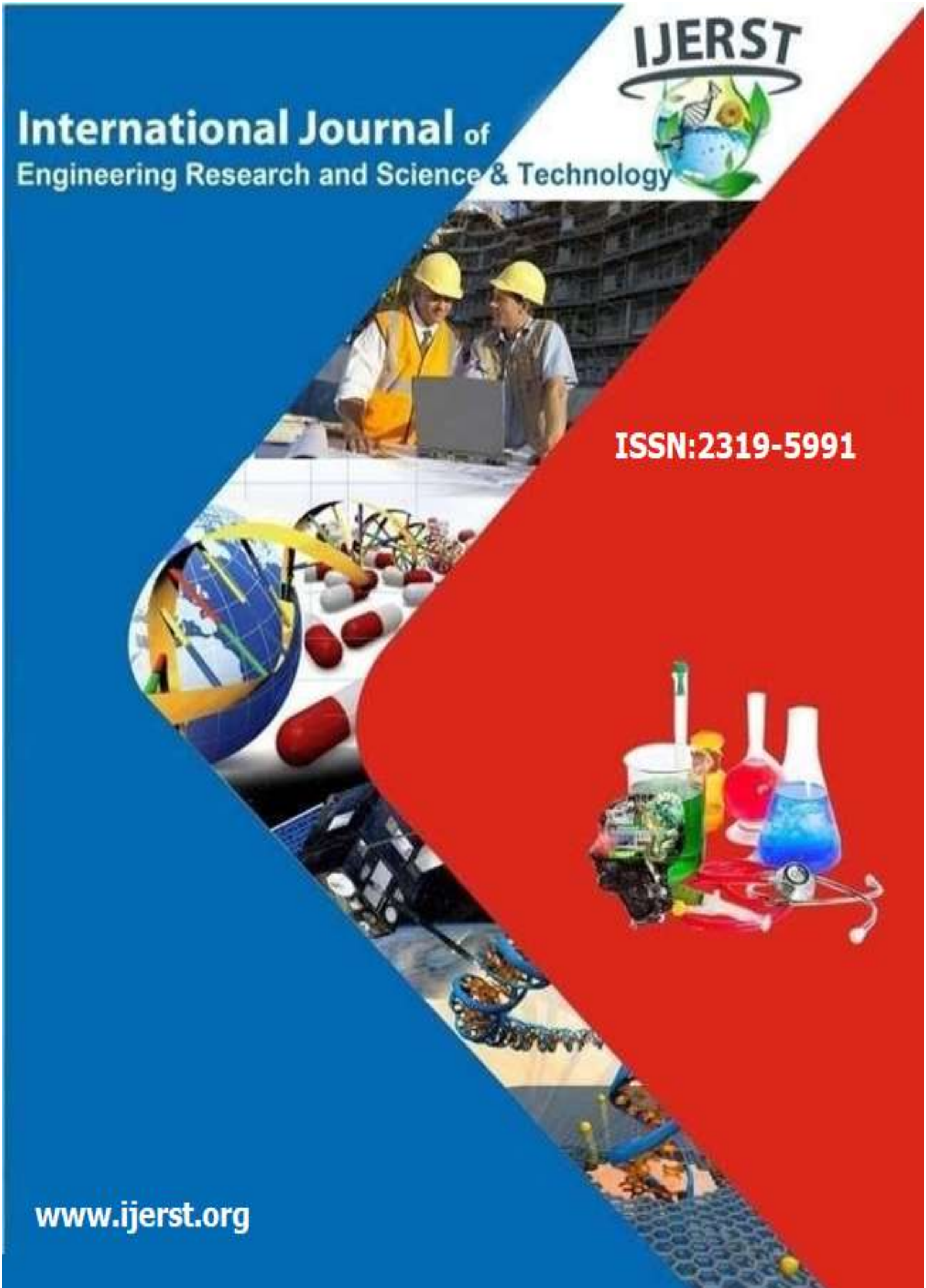

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MECHANICAL PROPERTIES OF TRANSLUCENT CONCRETE

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ABSTRACT: This research explores the development of Light-Transmitting Concrete with Optical Fibers Lighttransmitting concrete, also known as translucent concrete, is a innovative building material that combines the strength of concrete with the ability to transmit light. This is achieved by incorporating optical fibers, such as glass or plastic fibers, into the concrete mixture. The addition of optical fibers enables the transmission of light through the concrete, creating a unique aesthetic effect. The study investigates the development of light-transmitting concrete by incorporating optical fibers at varying percentages (1%, 1.5%, and 2% by volume). The concrete mixture consists of cement, sand, aggregate, and optical fibers. The mechanical properties of the concrete are investigated through various tests, including compressive strength, split tensile and flexural test. The results show that the compressive strength of the concrete decreases slightly with increasing fiber content. This is due to the reduced density of the concrete caused by the addition of optical fibers. However, the light-transmitting properties of the concrete improve significantly with increasing fiber content.

1. INTRODUCTION

With the rapid development of modern cities and advancements in science and technology, civil engineering has seen a dramatic shift towards smart, sustainable, and energy-efficient structures. Highrise buildings, underground facilities, and landmark architectural projects are becoming more common across the globe. However, this economic and infrastructural growth often brings challenges, especially in terms of high energy consumption, environmental impact, and building safety. One of the major concerns in modern construction is the overuse of artificial lighting, especially in interior spaces with limited natural light access. This dependence on electric lighting not only increases energy demands but also contributes to pollution and higher operational costs. To address these issues, engineers and architects have started exploring new types of materials that can support energy efficiency, durability, and structural intelligence. Among the most promising innovations is the development of transparent concrete—a unique material that combines the strength of traditional concrete with the lighttransmitting properties of optical fibers. Introduced in 2001 by Hungarian architect Áron Losonczi, this concept led to the creation of the first transparent concrete block, known as LiTraCon (Light Transmitting Concrete), in 2003. Transparent concrete is produced by embedding a small percentage (around 5%) of optical glass fibers into fine concrete. These fibers act as light conductors, allowing natural or artificial light to pass through the material. This not only reduces the need for artificial lighting during the daytime but also enhances the aesthetics and visual appeal of buildings. The fibers are arranged in a matrix parallel to the concrete surfaces, forming channels that can transmit light from one side of a wall to the other, even up to a thickness of 20 meters. Despite being translucent, this innovative material maintains the mechanical strength of regular concrete, making it suitable for both structural and decorative applications. It can be used in interior walls, exterior façades, pavements, and design elements, offering a futuristic look while supporting sustainable construction practices. The integration of optical fibers into concrete represents a new direction in civil engineering—where energy-saving, intelligence, and aesthetics come together. As cities grow and demand smarter infrastructure, materials like transparent concrete offer a promising

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solution for a brighter, lighter, and more efficient built environment.

1.1 SCOPE OF WORK

The scope of this work focuses on exploring the concept, development, characteristics, and practical applications of transparent concrete in modern civil engineering, with special emphasis on the integration of optical fibers to enhance light transmission, sustainability, and energy efficiency. This study aims to offer a comprehensive understanding of how transparent concrete can contribute to the transformation of traditional building materials into smart, eco-friendly, and aesthetically advanced alternatives suitable for contemporary construction needs. The project also aims to analyze the **manufacturing process**, including the types of fibers used (plastic), orientation techniques, and the overall preparation of transparent concrete blocks and panels. The research includes evaluating the **technical performance** of this material, such as compressive strength, durability and resistance to environmental factors, to determine its suitability for various structural and non-structural applications.

1.2 OBJECTIVES OF THE STUDY

- **Understanding the Composition**: To study the combination of fine concrete and optical fibers, and how their integration allows the passage of light through concrete structures.
- **Analysing the Manufacturing Process**: To explore the step-by-step procedure involved in producing transparent concrete blocks, including the placement and orientation of optical fibers. • **Evaluating Mechanical Properties**: To compare the strength and durability of transparent concrete with conventional concrete, ensuring that structural integrity is not compromised.
- **Identifying Applications**: To examine various practical uses of transparent concrete in both structural and non-structural components such as walls, pavements, and decorative features.
- **Assessing Energy Efficiency**: To investigate how the use of light-transmitting materials can reduce dependency on artificial lighting and promote sustainable building practices.
- **Exploring Architectural Aesthetics**: To highlight the visual and artistic potential of transparent concrete in enhancing building design and interior spaces.
- **Daylight Harvesting and Energy Efficiency**: Assess how transparent concrete can reduce the need for artificial lighting, especially in daylight hours.

2. LITERATURE REVIEW

2.1 An Experimental Study on Light Transmitting Concrete by P.M.Shanmugavadivu, V. Scinduja, T. Sarathivelan, C.V Shudesamithronn.

The paper titled *"An Experimental Study on Light Transmitting Concrete"* investigates the development, strength performance, and practical applications of light transmitting concrete (LTC), a modern construction material that combines traditional concrete with optical fibers to allow light to pass through its body. This innovative material was inspired by the concept introduced by Hungarian architect Áron Losonczi through LiTraCon in 2003. The study aims to evaluate both the decorative and structural benefits of embedding optical fibers—specifically end-lit plastic fibers—into concrete. The researchers used Portland Pozzolana Cement, natural sand, and optical fibers in a specific mix ratio (360 kg cement, 560 kg sand, 4.5 kg fiber, and 190 liters of water) to prepare the LTC. Fibers were arranged in patterns before casting, and slabs were cured and connected to light sources for testing. The workability of the mix was determined using a slump cone test, showing a slump of 92 mm. Strength tests showed that LTC maintained a compressive and flexural strength comparable to normal M20 grade concrete, confirming that the integration of optical fibers did not significantly weaken

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the material. On the contrary, LTC provided both structural efficiency and enhanced visual aesthetics. The concrete could transmit light effectively, making it suitable for interior walls, ceilings, panels, pavements, and decorative architectural features. It also demonstrated potential for reducing energy consumption by allowing daylight into buildings. The study concluded that LTC is not only a decorative element but also a structurally reliable and eco-friendly material for modern, smart, and sustainable buildings.

2.2 An Experimental Study by Ismail Luhar, Salmabanu Luhar , Pericles Savva , Antreas Theodosiou , Michael F. Petrou and Demetris Nicolaides.

The article "Light Transmitting Concrete: A Review" presents a comprehensive analysis of translucent or light-transmitting concrete (LTC), a modern and innovative construction material that integrates optical fibers within concrete to transmit light. This technology enhances architectural aesthetics and promotes green building practices by reducing the need for artificial lighting and improving energy efficiency. The review explores the working principles, particularly the role of optical fibers in channeling light through total internal reflection. It also evaluates various properties of LTC, including mechanical strength, thermal insulation, energy savings, and durability. Despite its benefits—such as improved daylight use, structural safety in dark environments like tunnels or prisons, and aesthetic value—LTC faces challenges like high production costs and limited industrial adoption. The paper emphasizes the need for further research, especially on the mechanical and microstructural properties of LTC, to optimize its design and encourage broader use in construction. The study concludes that LTC holds great promise as a sustainable, energy-efficient, and visually appealing building material for the future.

2.3 An Experimental Study by Keerthana, Mani, Srilatha, Prashanth, Rakesh

The study titled "Study on Light Transmitting Concrete" explores a modern type of concrete known as *light transmitting concrete* or *translucent concrete*, which incorporates glass rods or optical fibers to allow light to pass through. This innovative material is lighter than traditional concrete and offers benefits such as lower density, better thermal insulation, and reduced energy consumption. The main focus of the research was to design and analyze concrete blocks by adding different percentages (0%, 1%, 1.3%, 1.6%, 1.9%) of plastic optical fibers (POFs), and assess their physical and mechanical properties.

The experiment included preparing 100mm cube specimens, testing for compressive strength and light transmittance, and analyzing density. Results showed that as the percentage of POF increased, the light transmittance improved, making it more efficient for daylight usage and reducing dependence on artificial lighting. However, this also led to a decrease in the compressive strength and density of the concrete. Despite this trade-off, light transmitting concrete is seen as a promising material for sustainable construction and green buildings, offering energy-saving potential and aesthetic appeal for modern infrastructure.

3.MATERIALS AND METHODOLOGY

3.1 General

The materials used in this study to develop light-transmitting concrete included Ordinary Portland Cement (OPC), fly ash, optical fibers (2 mm diameter), fine aggregate (4.75 mm), coarse aggregate (10 mm), and clean water. Cement served as the primary binder, while fly ash was used as a partial replacement to improve workability and reduce environmental impact. The fine aggregate used was natural sand with a maximum size of 4.75 mm, and the coarse aggregate had a size of 10 mm, both selected according to standard specifications. Optical fibers with a diameter of 2 mm were incorporated to enable light transmission through the concrete, enhancing its architectural and functional appeal.

Clean, potable water was used to ensure proper mixing and hydration.

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The procedure began by weighing and mixing the dry components—cement, fly ash, fine and coarse aggregates—in a concrete mixer until a uniform consistency was achieved. Water was then gradually added to form a workable concrete mix. The 2 mm optical fibers were cut to the required length and placed horizontally and uniformly within the molds before pouring the concrete. Care was taken to ensure the fibers remained straight and evenly spaced. After casting, the specimens were left undisturbed for 24 hours and then cured in water for 28 days. Post-curing, the specimens underwent tests for compressive strength and light transmittance to evaluate the structural and functional performance of the concrete.

3.2 Materials Used

Cement

Cement used in the experimental work is ordinary Portland cement of 53 Grade conforming to IS: 12269-1987, The physical properties & chemical properties of the cement per IS: 12269-2013. Cement is a binding material used in construction that hardens and sets to hold materials together. The most commonly used type is Ordinary Portland Cement (OPC), which consists mainly of lime (CaO), silica (SiO_2), alumina (Al_2O_3), and iron oxide (Fe_2O_3). It is mixed with water and aggregates to form concrete, a strong material used in building structures. Cement can also be combined with other materials like fly ash or gypsum to improve properties such as durability and strength.

Physical Properties

Physical Property	Value
Compressive Strength	53 MPa (after 28 days)
Fineness	225-350 m²/kg (Blaine fineness test)
Initial Setting Time	Minimum 30 minutes
Final Setting Time	Maximum 600 minutes
Soundness (Le Chatelier Test)	Maximum 10-12 mm (expansion ltd)
Specific Gravity	3.10 - 3.15
Bulk Density	1440 - 1500 kg/m³
Water Demand	23-28% of weight (dependent on the water-cement ratio)
Heat of Hydration	Moderate
Colour	Grey
Drying Shrinkage	Typically, 0.02% to 0.08%

Chemical Properties

Chemical Component	Percentage (%)
Lime (CaO)	60-65%
Silica (SiO_2)	20-25%
Alumina (Al_2O_3)	4-8%
Iron Oxide (Fe_2O_3)	2-5%
Alkalis (Na_2O + K_2O)	Maximum 0.6%

Fly-Ash

Fly-Ash is used as partial replacement by cement at ,35% we taken 35% replacement because we have done project on fly-ash replacement by some percentages replacements like (25%,25%,30%,35% & 40%) we got 35% higher strength where compare to other percentages ,taken class (C) fly-ash. Class C fly ash is typically high in calcium content, making it self-cementing. Class C fly ash is used as a partial replacement for cement in concrete production, requiring early strength and durability. Fly-Ash Enhances workability of concrete Improves durability and resistance to chemical attacks and environmentally friendly: Reduces cement consumption and minimizes waste also cost saving.

Physical Properties

Property	Value
Particle Size	10-100 µm
Specific Gravity	2.2 - 2.8
Fineness (Blaine)	300-600 m²/kg
Bulk Density	540-860 kg/m³
Color	Light grey to dark grey

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Chemical Properties

Chemical Component	Percentage (%)
Silicon Dioxide(SiO_2)	40-60%
Aluminum Oxide (Al_2O_3)	15-30%
Calcium Oxide (CaO)	10-40%
Iron Oxide (Fe_2O_3)	4-15%
Magnesium Oxide (MgO)	1-5%

Coarse aggregates

Crushed Granite of 10mm maximum size has been used as coarse aggregate. The sieve analysis of combined aggregates confirms to the specifications of IS 383: 1970 for graded aggregates.

- Specific gravity =2.64
- Fineness Modulus = 6.816

Fine aggregates

Fine aggregate was purchased which satisfied the required properties of fine aggregate required for experimental work and the sand conforms to zone III as per the specifications of IS 383: 1970.

Taken 4.74mm fine aggregate.

- Specific gravity = 2.6
- Fineness modulus = 2.584

Water Water is an important ingredient of concrete as it actively participates in the chemical reaction with cement. Since it helps to form the strength giving cement gel, the quantity and quality of water is required to be looked in to very carefully. Mixing water should not contain undesirable organic substances or inorganic constituents in excessive proportion. Some specification also accept water for making concrete if the pH value of water lies between 6 and 8 and the water is free from organic matter. Carbonates and bi-carbonates of sodium and potassium effect the setting time of cement. While sodium carbonate may cause quick setting time, the bi-carbonates may either accelerate or retard the setting. The other higher concentration of these salts will materially reduce the concrete strength. In this study clean potable water was obtained from Department of Civil Engineering, Vidya Jyothi Institute of

Technology college, for mixing and curing of concrete.

Optical Fibers

Optical fibers are long, thin, and flexible strands usually made of plastic or glass that are designed to transmit light from one end to the other. In this project, 2 mm diameter optical fibers are used in concrete to create a light-transmitting effect. These fibers allow light to pass through the concrete, making the surface look bright and decorative, especially when exposed to sunlight or artificial light. The optical fibers are placed in straight lines inside the concrete molds before casting. They do not carry electricity and do not weaken the concrete structure. Instead, they help create a modern, ecofriendly, and energy-saving material used in buildings, pavements, and decorative walls.
Used optical fiber as percentage like 1%,1.5%,2% of cross-section of concrete mould as 4 mixes each mix done 6 cubes.

Sizes of Optical Fibers

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3.3 Wooden casting Mould

For casting the concrete specimens, wooden moulds of size 100 mm × 100 mm × 100 mm were used.

These standard cube moulds are commonly used for evaluating the compressive strength of concrete. To insert the optical fibers, 2 mm diameter holes were made on opposite sides of each mould. 2 mm optical fibers were passed through these holes and arranged in a straight and uniform pattern within the concrete block. A total of four different mix proportions were prepared with (0%, 1%, 1.5%, and 2%) optical fiber content by volume to study their effect on both light transmission and mechanical properties. The 0% mix served as the control specimen with no optical fibers, representing conventional concrete behavior. For each mix percentage, 6 cubes were cast—2 cubes each were tested after 7, 14, and 28 days of water curing. The moulds were properly cleaned and oiled before casting. After placing the fibers (where applicable), the concrete mix was poured and compacted thoroughly. The specimens were demoulded after 24 hours and then placed in a curing tank to ensure proper strength development.

In addition to cubes, concrete panels of size 200 mm × 200 mm × 40 mm were also cast to study the visual light-transmitting effect. For these panels, optical fiber percentages were varied at 2%, 4%, 6%, and 8% by volume to observe the increase in light transmission with higher fiber content. One panel was cast for each percentage, and all panels were cured in water for 28 days to ensure proper strength and bonding. Similar to the cubes, 2 mm diameter optical fibers were used and arranged in a straight, uniform pattern through holes made in the moulds. The moulds were prepared using wood, cleaned, and oiled before casting. After placing the fibers, the concrete mix was poured carefully and compacted to eliminate air voids. These panels were specifically prepared to visually demonstrate the potential of light-transmitting concrete for decorative and architectural purposes.

Fig: Wooden Mould With 2mm Optical Fibers

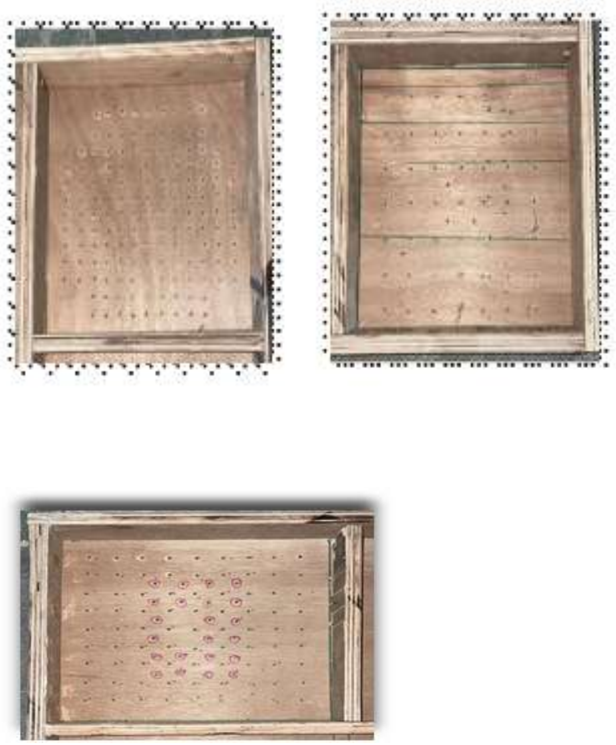

Fig: Wooden Panels Of Size (200mmx200mmx40mm)

3.4 Concrete Mix Ratio

M25 grade concrete is a standard concrete mix with a characteristic compressive strength of 25 MPa after 28 days of curing. It is commonly used in structural applications such as beams, slabs, columns, and foundations. The typical nominal mix ratio for M25 grade concrete is 1:1:2 (1 part cement: 1 part fine aggregate: 2 parts coarse aggregate) by volume. However, for higher accuracy and performance, design mix is often used, where the mix proportions are calculated based on requirements like

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workability, strength, and durability. M25 concrete offers a good balance between strength and workability, making it suitable for both residential and commercial construction projects.

3.5 Mixing of concrete

In this concrete mix design, 35% of the ordinary Portland cement (OPC) was replaced with fly ash, which is an eco-friendly byproduct of coal combustion in thermal power plants. Fly ash is widely recognized for its pozzolanic properties, meaning it reacts with calcium hydroxide in the presence of water to form additional cementitious compounds. This reaction enhances the long-term strength and durability of concrete, while also improving its workability and reducing the heat of hydration. By replacing a portion of the cement with fly ash, we not only minimize the environmental impact associated with cement production, which is a major source of carbon dioxide emissions, but also make use of industrial waste that would otherwise be disposed of in landfills.

To begin the mixing process, all the dry materials were measured accurately based on the mix design proportions. These dry materials included the cement (with 35% fly ash replacement), fine aggregate (natural river sand), and coarse aggregate (gravel or crushed stone). These materials were first thoroughly dry-mixed in a concrete mixer to achieve a uniform color and texture, ensuring that the fly ash was evenly distributed throughout the mixture. This step is essential to promote the homogeneity of the final concrete and prevent weak zones or segregation.

Once the dry mix was uniform, clean water was gradually added while the mixer was running. The mixing process continued until a consistent, workable, and cohesive concrete mix was achieved. The use of a mechanical concrete mixer helps ensure better blending and uniformity compared to manual mixing, especially for medium to large-scale construction projects. The water-cement ratio was carefully controlled to avoid excess water, which can reduce the strength and durability of the final product.

Overall, using fly ash as a partial replacement for cement in concrete production offers several advantages. It improves the workability of fresh concrete, enhances resistance to sulfate attack and alkali-silica reaction, and contributes to sustainability by conserving natural resources and reducing greenhouse gas emissions.

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3.6 Vibrating Table

A table vibrator is a mechanical device used during the casting of concrete to ensure proper compaction and eliminate air voids within the mix. It consists of a flat platform mounted on vibrating motors, which vibrate at a controlled frequency and amplitude. When concrete-filled molds are placed on the table and the machine is switched on, the vibrations cause the concrete to settle uniformly and compact properly. This process helps remove entrapped air and reduces the formation of voids or honeycombing, resulting in a denser and stronger final product. Table vibrators are especially useful in the preparation of precast concrete elements such as tiles, pavers, and laboratory test samples. They significantly improve the surface finish and compressive strength of the concrete by ensuring that the material is evenly distributed throughout the mold. However, care must be taken not to over-vibrate, as this can lead to segregation of the concrete components. Proper vibration time, usually between 30 seconds to 2 minutes depending on the mix, should be maintained to achieve optimal results.

Fig : Table Vibrator

Fig : Casted Cubes

Compressive Strength Test

The Compressive Strength Test was conducted to evaluate the concrete's resistance to crushing loads, especially when modified with varying amounts of optical fibres. Concrete cubes of 100 mm × 100 mm × 100 mm were cast using M25 grade concrete, and optical fibres of 2mm were added at 0%, 1%, 1.5%, and 2% by volume. For each percentage, six specimens were prepared, resulting in a total of twenty-four cubes. The 0% fibre specimens served as control samples to compare the impact of fibre inclusion on strength. All specimens were cured under

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standard conditions and tested at 7, 14, and 28 days using a Universal Testing Machine (UTM). In the mix, 35% of the cement was replaced with fly ash, an eco-friendly material that enhances workability and long-term durability while reducing the environmental impact of cement production. The mix also used fine aggregate of 4.75 mm and coarse aggregate of 10 mm, ensuring proper grading and bonding within the concrete. This comprehensive testing setup allowed for a detailed analysis of the effect of optical fibre content, fly ash replacement, and curing duration on the compressive strength of concrete.

Fig: Compressive Test

Compressive Strength Result Test Results

7 Days Compressive Strength Results Table

Optical Fiber %	**0%**	**1%**	**1.5%**	**2%**
Cube - 1	28.58	26.94	24.87	23.93
Cube - 2	27.62	25.81	26.62	24.92
Avg.	**28.10**	**26.37**	**25.74**	**24.42**

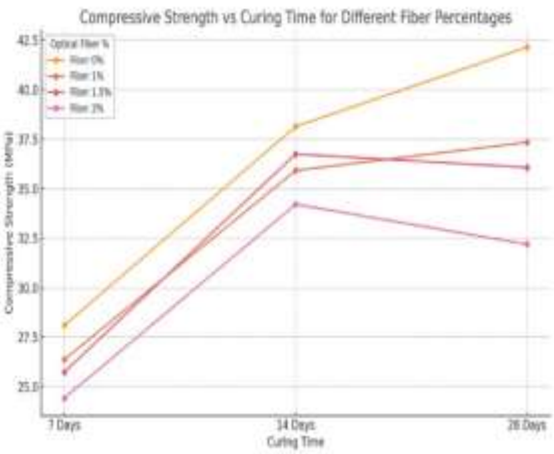
14 Days Compressive Strength Table

Optical Fiber %	**0%**	**1%**	**1.5%**	**2%**
Cube - 1	37.46	34.59	35.96	33.04
Cube - 2	38.81	35.92	37.55	32.21
Avg.	**38.14**	**35.92**	**36.75**	**32.63**

28 Days Compressive Strength Table

Optical Fiber %	**0%**	**1%**	**1.5%**	**2%**
Cube - 1	41.32	36.45	35.89	33.58
Cube - 2	42.99	38.24	36.25	30.80
Avg.	**42.15**	**37.34**	**36.07**	**32.19**

Graphs Related to Results



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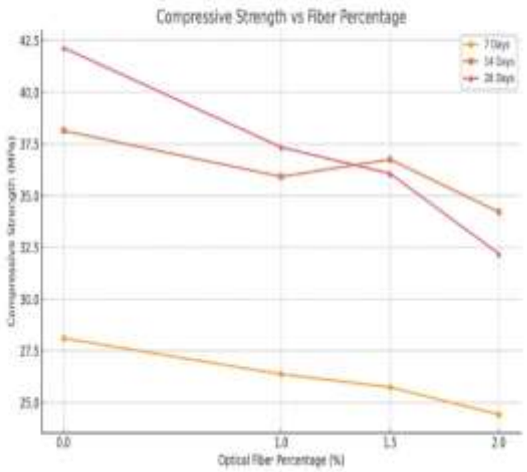

Split-Tensile Strength Test

The Split-Tensile Strength Test is a method used in civil engineering to determine the tensile strength of concrete. Since concrete is naturally weak in tension, this test is important for understanding how well it can resist forces that try to pull it apart. In this test, a cylindrical concrete specimen, usually 150 mm in diameter and 300 mm in height, is placed horizontally in a testing machine. A compressive load is then applied along the vertical diameter of the cylinder. This load creates tensile stress across the horizontal plane of the cylinder, causing the specimen to split vertically. The test does not directly apply tension but induces it indirectly through compression, making it a practical and effective way to measure the tensile strength of concrete. The result helps engineers design concrete structures that can better resist cracking and failure under tensile forces.

Split-Tensile Strength Test In (Mpa)

Fiber %	7Days	14Days	28Days
0%	0.562	2.28	2.95
1%	2.10	1.79	1.49
1.5%	1.28	1.102	2.16
2%	1.95	2.28	2.89

Flexural strength test

The Flexural Strength Test is a method used to determine the ability of concrete to resist bending or flexural stress. It measures the tensile strength of concrete in bending, which is important for structures like beams, pavements, and slabs, where bending forces are common. In this test, a concrete beam specimen, usually with dimensions 150 mm × 150 mm × 700 mm, is supported at both ends and loaded at one or two points along the span. As the load increases, the beam bends, and eventually, it breaks. The maximum load at failure is used to calculate the modulus of rupture, which represents the flexural strength of the concrete. This test helps engineers understand how much bending stress a concrete member can handle before cracking or failing, and it plays a crucial role in the design of structural elements subjected to flexural loads.

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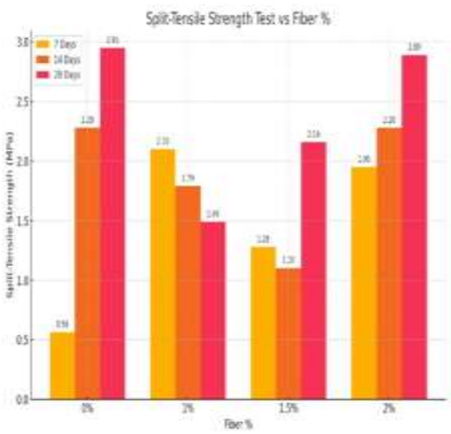
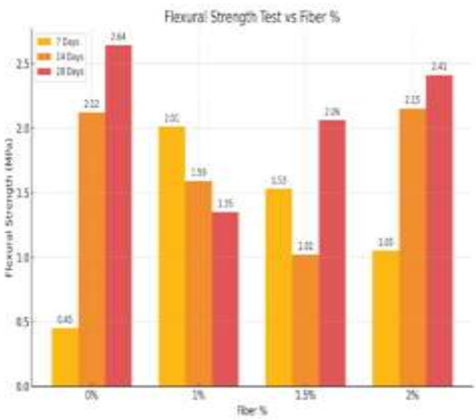
Flexural Strength Test In Mpa

Fiber %	7Days	14Days	28Days
0%	0.45	2.12	2.64
1%	2.01	1.59	1.35
1.5%	1.53	1.02	2.06
2%	1.05	2.15	2.41





4. CONCLUSION

The compressive strength test was conducted to assess the performance of concrete with varying percentages of fiber (0%, 1%, 1.5%, and 2%) over different curing periods—7, 14, and 28 days. The findings provide clear insights into the influence of fiber content on the compressive strength of concrete.

4.1Effect of Fiber Content on Compressive Strength

Across all curing durations, the results consistently show that concrete without any fiber (0% fiber) achieved the highest compressive strength values. As the fiber content increased, the compressive strength decreased progressively:

- **At 7 Days:**
  - 0% Fiber: 28.10 MPa
  - 1% Fiber: 26.37 MPa
  - 1.5% Fiber: 25.74 MPa
  - 2% Fiber: 24.42 MPa
- **At 14 Days:**
  - 0% Fiber: 38.14 MPa
  - 1% Fiber: 35.92 MPa
  - 1.5% Fiber: 36.75 MPa (notably higher than 1% and 2%)
  - 2% Fiber: 32.63 MPa
- **At 28 Days:**

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- 0% Fiber: 42.15 MPa
- 1% Fiber: 37.34 MPa
- 1.5% Fiber: 36.07 MPa
- 2% Fiber: 32.19 MPa

4.2. Interpretation of Results

- The compressive strength of concrete naturally increases with curing time, as expected, due to the continued hydration process.
- The addition of fiber appears to interfere with the development of compressive strength. This may be due to:
  - The fibers creating microvoids or weak interfaces within the concrete matrix.
  - Difficulty in achieving a uniformly compacted mix at higher fiber contents.
- Interestingly, at **14 days**, the sample with **1.5% fiber** showed slightly higher compressive strength than 1%, suggesting that at intermediate durations, a moderate fiber content might offer a balance between structural integrity and other mechanical benefits.
- The results show that the compressive, split-tensile, and flexural strengths of concrete generally increase with curing time due to ongoing hydration. While the addition of fibers initially enhances tensile and flexural strength, it may reduce compressive strength due to the formation of microvoids or poor compaction. In the split-tensile test, 1% fiber gave the highest strength at 7 days, but strength declined over time, whereas 2% fiber maintained high values throughout. Flexural strength was highest for 1% fiber at 7 days but decreased by 28 days, while 2% and 1.5% fibers showed better long-term performance. Overall, 1.5% to 2% fiber content appears to offer the best balance of strength over time.

4.3. Optimal Fiber Content

From a compressive strength perspective, **0% fiber** yields the best results. However, if fiber reinforcement is necessary for other reasons (e.g., crack control, toughness, impact resistance), a **lower percentage (around 1%–1.5%)** might be considered optimal, depending on project requirements.

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