EXPERIMENTAL STUDY ON MECHANICAL AND DURABILITY PROPERTIES OF CONCRETE REINFORCED WITH SOLAR PANEL BACKSHEET FIBER

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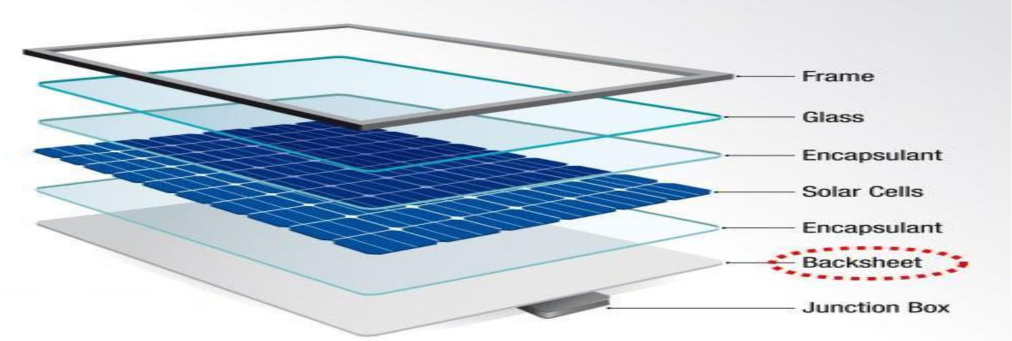
ABSTRACT: *The rapid expansion of photovoltaic (PV) energy systems worldwide has resulted in a significant increase in end-of-life solar panel waste, posing serious environmental and disposal challenges. Among the various components of photovoltaic modules, the polymeric backsheet layer is particularly problematic due to its multilayer composition, chemical resistance, and non-biodegradable nature. Conventional disposal methods such as landfilling and incineration are environmentally unsustainable. In this context, the present study explores an innovative and sustainable approach by reutilizing solar panel backsheet waste as discrete fiber reinforcement in concrete. In this experimental investigation, backsheet materials extracted from discarded photovoltaic panels were processed into short fibers of approximately 12 mm length and incorporated into M30 grade concrete at varying volume fractions of 0%, 0.5%, 1.0%, and 1.5%. The influence of fiber addition on fresh, mechanical, and durability properties of concrete was systematically evaluated. Mechanical properties assessed include compressive strength at 7 and 28 days, split tensile strength, and flexural strength. Durability performance was examined through water absorption, sorptivity, and acid resistance tests. The results demonstrate that incorporation of solar panel backsheet fibers significantly enhances tensile and flexural performance due to improved crack-bridging mechanisms and stress redistribution within the concrete matrix. Compressive strength showed marginal improvement up to an optimum fiber dosage of 1.0%, beyond which a slight reduction was observed due to decreased workability and compaction efficiency. Durability parameters indicated reduced permeability and improved resistance to aggressive environments in fiber reinforced specimens compared to conventional concrete. The study confirms that solar panel backsheet waste can be effectively valorized as a sustainable reinforcement material in concrete, contributing to waste minimization, resource conservation, and advancement of environmentally responsible construction practices.*

Keywords: Solar panel waste, Backsheetfiber, Fiber reinforced concrete, Mechanical properties, Durability performance, Sustainable construction.

1. INTRODUCTION

The global transition toward renewable energy has significantly accelerated the installation of photovoltaic (PV) systems. While solar energy is environmentally friendly during operation, the management of end-of-life PV panels has emerged as a critical environmental issue. Solar panels typically have a service life of 20–25 years, after which disposal or recycling becomes necessary. It is estimated that millions of tonnes of PV waste will be generated globally in the coming decades. A solar panel consists of glass, aluminum frame, silicon cells, encapsulant layers, and a polymeric backsheet. The backsheet layer, which provides electrical insulation and environmental protection, is generally composed of multilayer polymer films such as PET combined with fluoro polymers. Due to their composite nature and chemical stability, these materials are difficult to recycle and are often disposed of in landfills.

Simultaneously, the construction industry is seeking sustainable alternatives to improve material performance while reducing environmental impact. Fiber Reinforced Concrete (FRC) has gained considerable attention for enhancing tensile strength, ductility, crack resistance, and impact resistance. Synthetic fibers such as polypropylene, polyester, and recycled plastic fibers have shown promising results in improving concrete performance. However, limited research has focused specifically on the reuse of solar panel backsheet waste in concrete. Therefore, this study aims to experimentally evaluate the feasibility of incorporating solar panel backsheet fibers in concrete and to analyze their influence on mechanical and durability properties.



2. OBJECTIVES OF THE STUDY

The primary objectives of this experimental investigation are

1. To evaluate the influence of solar panel backsheet fiber incorporation on the mechanical properties of concrete, particularly compressive strength, split tensile strength, and flexural strength.
2. To assess the durability performance of backsheet fiber reinforced concrete through water absorption, sorptivity, and acid resistance tests.
3. Optimum fibre content.

3. MATERIALS USED

3.1 Cement

Ordinary Portland Cement (OPC) of 53 Grade conforming to IS 12269 was used in the present investigation. Cement acts as the primary binding material in concrete and plays a crucial role in determining strength and durability characteristics. The selection of 53 Grade cement ensures adequate early strength development and suitability for M30 grade concrete.The specific gravity of cement was found to be approximately 3.15, which falls within standard permissible limits. The fineness of cement influences hydration rate and strength gain. Proper storage conditions were maintained to prevent moisture absorption and lump formation prior to use.

The initial and final setting times of cement were within codal limits, ensuring sufficient working time during mixing and placement.

Soundness of cement was verified to avoid excessive expansion due to free lime content.Cement hydration produces calcium silicate hydrate (C-S-H) gel, which is primarily responsible for strength development in concrete. The interaction between cement paste and fiber reinforcement is also influenced by the hydration process. In fiber reinforced concrete, cement matrix plays an important role in bonding with fibers. Adequate paste content is necessary to ensure proper encapsulation of fibers and uniform stress distribution.The choice of high-quality OPC helps maintain consistency in experimental results and ensures reliable comparison between control and fiber reinforced mixes.

3.2 Fine Aggregate

Fine aggregate used in this study was natural river sand conforming to Zone II as per IS 383 specifications. Fine aggregate occupies approximately 30–40% of total concrete volume and significantly influences workability and strength characteristics. The sand was clean, well-graded, and free from organic impurities, clay, silt, and deleterious materials. Proper grading ensures better particle packing and reduced void content in concrete. The specific gravity of fine aggregate was approximately 2.65. Water absorption capacity was within permissible limits, ensuring minimal variation in effective water-cement ratio.

The fineness modulus of sand plays an important role in determining workability. A balanced gradation improves cohesiveness and reduces bleeding and segregation.

In fiber reinforced concrete, fine aggregate helps in improving fiber dispersion. Well-graded sand prevents fiber clustering and promotes uniform distribution throughout the concrete matrix. The quality of fine aggregate directly affects durability properties such as permeability and sorptivity. Therefore, careful selection and testing of sand were carried out prior to use.

3.3 Coarse Aggregate

Crushed granite coarse aggregate of maximum nominal size 20 mm was used in this investigation. Coarse aggregate forms the skeletal structure of concrete and contributes significantly to compressive strength. The aggregates were angular in shape, which enhances interlocking and improves mechanical strength. The specific gravity was approximately 2.70, and water absorption was within standard limits.

Aggregate crushing value and impact value tests indicated satisfactory mechanical properties suitable for structural grade concrete.Proper washing and drying were carried out before mixing to remove dust particles. Clean aggregate surfaces ensure better bonding with cement paste.In fiber reinforced concrete, coarse aggregate distribution influences fiber orientation and crack propagation behavior.The use of high-quality granite aggregate ensures that any variation in results is primarily due to fiber addition rather than aggregate defects.

3.4 Solar Panel Backsheet Fiber

Solar panel backsheet material was obtained from discarded photovoltaic modules. The panels were manually dismantled to separate the backsheet layer from glass and other components. The extracted backsheet sheets were cleaned to remove adhesive residues and dust particles. The material was then cut into short discrete fibers of approximately 12 mm length using mechanical cutting tools. The backsheet is primarily composed of multilayer polymer films such as PET combined with fluoro polymer coatings. These materials exhibit high chemical resistance, low moisture absorption, and good flexibility.

The density of the backsheet fiber is lower than steel fibers, which makes it lightweight and easier to handle during mixing. The fibers are non-corrosive in nature, making them suitable for use in aggressive environments. The smooth surface texture may influence bonding characteristics; however, mechanical interlocking and crack-bridging effects contribute to performance enhancement. The use of solar panel backsheet fiber not only improves concrete properties but also contributes to waste minimization and sustainable resource utilization.

3.5 Water

Potable water free from impurities, oils, acids, alkalis, and organic matter was used for mixing and curing of concrete. Water plays a critical role in cement hydration and workability. The water–cement ratio significantly influences strength and durability performance. Proper curing was carried out to ensure complete hydration and strength development. In durability tests, consistent water quality ensures accurate comparison between mixes.

4. MIX DESIGN AND PROPORTIONING

The concrete mix was designed for M30 grade in accordance with IS 10262:2019 and IS 456:2000 provisions. The target mean compressive strength was calculated considering a standard deviation of 5 MPa. The water–cement ratio was fixed at 0.45 to ensure adequate strength and durability under moderate exposure conditions.

The mix design process included determination of:

- Target mean strength
- Selection of water–cement ratio
- Estimation of water content
- Calculation of cement content
- Proportioning of fine and coarse aggregates
- Adjustment for fiber inclusion

Trial mixes were conducted to achieve optimum workability and mechanical performance. The control mix was prepared without fiber addition and served as the reference mix (CM). Solar panel backsheetfibers were incorporated at volume fractions of 0.5%, 1.0%, and 1.5%.

Since fiber addition affects volume distribution, slight adjustments were made to aggregate content to maintain overall volume consistency.

4.1 Mix Proportion Details (Per Cubic Meter)

Mix ID	Cement (kg/m^3)	Fine Agg (kg/m^3)	Coarse Agg (kg/m^3)	water (kg/m^3)	Fiber (kg/m^3)
CM	414	615	1164	186	0.00
SPF-0.5	414	615	1164	186	2.07
SPF-1.0	414	615	1164	186	4.14
SPF-1.5	414	615	1164	186	6.21

Water–Cement Ratio = 0.45
(Note: Minor reduction in aggregate content accounts for fiber volume replacement.)

4.2 Justification For Mix Selection

The cement content of 400 kg/m^3 was selected to ensure adequate paste availability for proper fiber encapsulation and bonding. A sufficient paste matrix is essential in fiber reinforced concrete to prevent fiber pull-out and ensure effective stress transfer. The fine aggregate proportion was optimized to improve cohesiveness and reduce segregation in the presence of fibers. Proper sand content ensures better dispersion of fibers and prevents clustering. The coarse aggregate content was slightly reduced in fiber reinforced mixes to compensate for the additional fiber volume and maintain total volume consistency per cubic meter.

The water content was kept constant across all mixes to ensure uniform comparison. Since fibers tend to reduce workability, careful mixing and compaction procedures were adopted instead of increasing water content, which could compromise strength. The chosen fiber percentages (0.5%, 1.0%, and 1.5%) were selected based on practical limits observed in polymer fiber reinforced concrete studies. Lower percentages may not produce significant performance enhancement, while higher percentages may adversely affect workability and compaction.

The mix proportions were finalized after preliminary trials that ensured:

- Acceptable slump range
- Uniform fiber dispersion
- No significant balling effect
- Adequate compaction
- Surface finish without honeycombing

4.3 Fresh Concrete Observations During Mixing

During mixing, it was observed that fiber incorporation increased internal friction within the concrete matrix. The mix became slightly stiffer as fiber content increased. However, no severe balling effect was observed up to 1.0% fiber dosage. At 1.5% fiber content, minor fiber clustering was noticed, which required additional mixing time to ensure uniform distribution. The concrete remained cohesive without noticeable segregation or bleeding. Proper vibration during casting ensured elimination of entrapped air and improved surface finish.

5. EXPERIMENTAL METHODOLOGY

5.1 Workability Assessment

Workability of fresh concrete was evaluated using the slump cone test in accordance with IS 1199. Workability is a crucial property that determines ease of mixing, placing, and compaction of concrete.

The slump cone was filled in three layers, each layer being tamped uniformly. After lifting the cone vertically, the reduction in height of concrete was measured as slump value. Fiber incorporation generally reduces workability due to increased surface area and interlocking between fibers. Monitoring slump variation helps in understanding the practical feasibility of fiber addition. The influence of fiber content on flow characteristics was carefully recorded and compared with control mix. Maintaining adequate workability is important to avoid honeycombing and ensure proper bonding between fibers and cement matrix.

5.2 Compressive Strength Test

Compressive strength is the most fundamental property of concrete and is used to evaluate its load carrying capacity. Cube specimens of 150 × 150 × 150 mm were cast for each mix proportion. Three specimens were tested at 7 days to evaluate early strength gain and three at 28 days to determine characteristic strength. Testing was conducted using a calibrated compression testing machine (CTM). Load was applied uniformly until failure. The average strength of three specimens was recorded to minimize experimental variation. The failure pattern of fiber reinforced specimens was observed to be less brittle compared to control concrete. The crack pattern indicated improved energy absorption capacity due to fiber bridging. The variation in compressive strength with fiber content was carefully analyzed to determine optimum dosage.

5.3 Split Tensile Strength Test

Concrete is weak in tension and prone to cracking. Therefore, evaluation of tensile strength is important for structural applications. Cylindrical specimens were cast and cured for 28 days. The split tensile test was conducted by placing the cylinder horizontally in the compression testing machine. Load was applied along the diameter until splitting failure occurred. Fiber reinforced specimens showed delayed crack propagation compared to control concrete. The presence of backsheet fibers enhanced post-cracking load carrying capacity. The tensile strength improvement is primarily attributed to crack arresting and stress transfer mechanism provided by fibers.

5.4 Flexural Strength Test

Flexural strength test evaluates the bending resistance of concrete, which is critical for pavements, beams, and slabs. Beam specimens were subjected to two-point loading until failure. The load at first crack and ultimate failure was recorded. Fiber reinforced beams exhibited improved ductility and reduced crack width compared to control specimens. The fibers bridged cracks and prevented sudden brittle failure. Flexural strength results are important in assessing suitability for structural elements subjected to bending stresses.

5.5 Durability Tests

Durability performance determines long-term behavior of concrete under environmental exposure.

5.5.1 Water Absorption

Water absorption test was conducted to evaluate permeability characteristics. Specimens were oven dried and then immersed in water for 24 hours. Weight difference was measured to determine absorption percentage. Lower water absorption indicates denser matrix and better durability. Fiber reinforced mixes showed reduced water absorption due to improved crack control.

5.5.2 Sorptivity

Sorptivity test measures capillary suction rate of water into concrete. Specimens were partially immersed and weight gain was measured at specific intervals. The rate of water absorption per unit area was calculated. Lower sorptivity values indicate improved resistance to moisture ingress. Fiber addition helped in reducing micro-cracks, thereby lowering capillary suction.

5.5.3 Acid Resistance

Acid resistance test evaluates chemical durability. Specimens were immersed in 5% sulfuric acid solution for 28 days. Weight loss and surface deterioration were observed. Fiber reinforced specimens showed improved resistance compared to control mix. Reduced permeability and crack control contributed to better acid resistance.

6. RESULTS AND DISCUSSION

The experimental results obtained from mechanical and durability tests are discussed in detail in this section. The influence of solar panel backsheet fiber addition on concrete performance is analyzed by comparing control and fiber reinforced mixes.

6.1 Workability

The slump values obtained for different mixes indicated a gradual reduction in workability with increasing fiber content. The control mix exhibited a slump value of approximately 90 mm, indicating good workability suitable for structural applications. With the addition of 0.5% backsheetfiber, the slump reduced moderately due to increased surface area and internal friction within the concrete matrix. At 1.0% fiber dosage, slump reduction was more noticeable but remained within acceptable limits for compaction using vibration.

At 1.5% fiber content, the slump value reduced significantly. This reduction is attributed to fiber interlocking and increased resistance to flow. The presence of discrete fibers restricts the mobility of aggregates and reduces flow ability.

Despite the reduction in slump, no severe segregation or bleeding was observed. Proper compaction techniques ensured adequate consolidation of the mix. The reduction in workability is a common phenomenon in fiber reinforced concrete and can be managed by proper mix design adjustments without increasing water content.

6.1 Workability Properties of Fresh Concrete

Workability of concrete plays a crucial role in determining the ease of mixing, placing, compacting, and finishing. In fiber reinforced concrete, workability is generally affected due to increased surface area and internal friction caused by fiber inclusion.

In this study, workability was evaluated using:

- Slump Cone Test
- Compaction Factor Test

Both tests were conducted as per IS 1199 guidelines.

6.1.1 Slump Test Results

The slump test was performed immediately after mixing to evaluate consistency of fresh concrete. The control mix exhibited good workability suitable for normal reinforced concrete applications

Table 6.1 Slump Values Obtained

Mix ID	Fiber Content (%)	Slump value (mm)
CM	0	92mm
SPF-0.5	0.5	82mm
SPF-1.0	1.0	70mm
SPF-1.5	1.5	58mm

Discussion on Slump Results. The control mix showed a slump value of 92 mm, indicating medium workability and good flow characteristics. With 0.5% fiber addition, slump reduced to 82 mm. This reduction is attributed to the increased surface area of fibers, which absorbs more cement paste and restricts free movement of aggregates.

At 1.0% fiber content, slump further reduced to 70 mm. The fibers create an interlocking network within the matrix, increasing internal friction and reducing flow ability.

At 1.5% fiber content, slump dropped to 58 mm. The reduction at higher fiber dosage is mainly due to fiber clustering and resistance to movement within the mix. However, even at 1.5%, the slump remained within workable limits for vibration compaction. No severe segregation or bleeding was observed.

The gradual reduction in slump confirms that solar panel backsheet fibers influence fresh concrete behavior but do not make the mix unworkable within the studied range.

6.1.2 Compaction Factor Test Results

The compaction factor test provides a more precise measure of workability for low to medium workable concrete mixes.

The compaction factor was calculated as:
Compaction Factor = (Weight of Partially Compacted Concrete) / (Weight of Fully Compacted Concrete)

Table 6.2 Compaction Factor Values

Mix ID	Fiber Content (%)	Compaction Factor
CM	0	0.92
SPF-0.5	0.5	0.89
SPF-1.0	1.0	0.86
SPF-1.5	1.5	0.83

Discussion on Compaction Factor Results

The control mix exhibited a compaction factor of 0.92, indicating good workability. At 0.5% fiber content, compaction factor reduced slightly to 0.89. This minor reduction suggests moderate resistance to compaction due to fiber presence. At 1.0% fiber content, the value decreased to 0.86. The reduction indicates increased stiffness of the mix. At 1.5%, compaction factor reached 0.83, confirming lower workability compared to control mix. The reduction trend observed in compaction factor values supports the slump test results. Both tests confirm that increasing fiber dosage reduces workability due to:

- Increased internal friction
- Higher surface area
- Fiber interlocking
- Reduced free water availability

However, compaction factor values above 0.80 indicate that the mix remains suitable for normal structural applications with mechanical vibration.

6.1.3 Overall Workability Interpretation

The combined analysis of slump and compaction factor results indicates that:

- Fiber addition reduces workability progressively.
- Up to 1.0% fiber content, the reduction is moderate and manageable.
- At 1.5%, workability becomes relatively low but still within acceptable limits.

Therefore, from workability perspective, 1.0% fiber dosage is considered optimal for balancing mechanical improvement and practical handling.

6.2 Compressive Strength

The compressive strength results at 7 and 28 days revealed that fiber addition influenced strength development. At 7 days, slight improvement in compressive strength was observed for 0.5% and 1.0% fiber content compared to control mix. This indicates that fiber inclusion does not adversely affect early hydration.

At 28 days, the mix containing 1.0% fiber exhibited the highest compressive strength among all mixes. The improvement can be attributed to crack-bridging action of fibers, which restricts micro-crack propagation under compressive loading.

The fibers act as stress arresters and help in redistributing internal stresses within the matrix. This results in delayed crack formation and enhanced load carrying capacity. However, at 1.5% fiber content, a slight reduction in compressive strength was observed. This reduction may be due to reduced workability leading to compaction difficulties and possible void formation. Overall, fiber addition up to 1.0% positively influenced compressive strength without compromising structural integrity.

6.3 Split Tensile Strength

The split tensile strength test demonstrated significant improvement in tensile capacity with fiber incorporation. Concrete is inherently weak in tension and prone to brittle failure. The presence of backsheet fibers enhanced resistance against crack initiation and propagation. At 0.5% fiber dosage, noticeable improvement in tensile strength was recorded. At 1.0%, the enhancement was substantial, indicating effective crack-bridging mechanism.

The fibers resist splitting by transferring tensile stresses across crack surfaces. This mechanism improves post-cracking behavior and energy absorption capacity. At 1.5% fiber dosage, tensile strength improvement was still observed but did not significantly exceed the 1.0% mix due to possible fiber clustering. The results confirm that solar panel backsheet fibers are effective in improving tensile performance of concrete.

6.4 Flexural Strength

Flexural strength results showed clear enhancement with fiber addition. Under bending load, cracks typically initiate at the tension zone of the beam. Fiber inclusion helped in bridging these cracks and delaying crack widening. The 1.0% fiber mix exhibited the highest flexural strength among all mixes. The load-deflection behavior indicated improved ductility and reduced brittle failure characteristics. The fibers increased energy absorption capacity and enhanced resistance against bending stresses. At higher fiber content (1.5%), flexural strength remained improved compared to control mix but did not significantly increase beyond the 1.0% mix. This suggests that 1.0% fiber dosage is optimal for achieving balanced performance.

6.5 Water Absorption

Water absorption test results indicated that fiber reinforced concrete exhibited lower water absorption compared to control concrete. The reduction in water absorption is attributed to improved crack control and better matrix integrity. Fibers help in minimizing micro-cracks that form during drying shrinkage. Reduced crack formation limits pathways for water ingress. Lower permeability directly enhances durability and resistance to aggressive environmental conditions.

6.6 Sorptivity

Sorptivity values decreased with fiber incorporation. The capillary suction rate was lower in fiber reinforced mixes, indicating improved resistance to moisture penetration. The fibers reduce interconnected pore structure by controlling crack development. Lower sorptivity contributes to long-term durability and improved service life of concrete structures.

6.7 Acid Resistance

In acid exposure conditions, control specimens showed greater surface deterioration and weight loss compared to fiber reinforced specimens. Fiber reinforced concrete demonstrated improved resistance to chemical attack due to reduced permeability and crack width. The presence of fibers limited acid penetration and reduced material degradation. These results indicate enhanced durability performance under aggressive environmental exposure.

7. CONCLUSIONS

Incorporation of solar panel backsheet fibers reduces workability; however, acceptable slump values were maintained up to 1.0% fiber dosage. Compressive strength improved up to 1.0% fiber addition due to crack-bridging mechanism and stress redistribution. Significant enhancement in split tensile and flexural strength was observed with fiber incorporation.

Fiber reinforced concrete exhibited improved ductility and reduced brittle failure characteristics. Water absorption and sorptivity values decreased with fiber addition, indicating improved durability. Acid resistance performance improved due to reduced permeability and crack control. The optimum fiber dosage was identified as 1.0% by volume of concrete. Solar panel backsheet waste can be effectively utilized as a sustainable fiber reinforcement material in concrete applications.

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