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ANALYSIS AND DESIGN OF BLOCKS USING END OF LIFE (EOL) SOLAR PANEL

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Abstract: The rapid expansion of solar energy systems has led to a growing concern regarding the disposal of end-of-life (EoL) solar panels. This study explores a sustainable approach for recycling waste glass and silica powder recovered from EoL photovoltaic (PV) modules for use in the production of concrete blocks. The glass and silica-rich materials, primarily derived from the encapsulant and glass layers of decommissioned solar panels, were processed and integrated as partial replacements for conventional fine aggregates and cement. The mechanical properties of concrete blocks were evaluated through compressive strength testing. The compressive strength of M25 grade concrete with a 12% partial replacement of fine aggregate with glass was evaluated at 7, 14, and 28 days of curing. The results showed a compressive strength of 16.113 N/mm² at 7 days, 32.24 N/mm² at 14 days, and 36.223 N/mm² at 28 days. While the 28-day strength surpassed the target of 25 N/mm² for M25 concrete This research contributes to sustainable waste management strategies and highlights the potential of EoL solar panels as a valuable secondary resource in construction material production. The durability and environmental impact are the further scope of research.

Keywords: solar panel, sustainability, photovoltaic (PV)modules.

1.Introduction:

The world currently faces a critical challenge in waste management as the volume of waste generated globally is increasing at an unprecedented rate. This rapid increase is driven by three major trends: rapid urbanization, exponential economic growth in developing countries and the widespread use of disposable consumer goods. The environmental consequences of this growing waste crisis are severe. The waste sector is a major contributor to climate change and environmental degradation due to inefficient waste handling, encompassing lost material value, cleanup expenses, and health-related costs linked to pollution. Ineffective waste management leads to escalating cleanup costs, higher landfill fees, and negative impacts on property values and local economies. Furthermore, lost opportunities in recycling and resource recovery diminish economic resilience and job creation in sustainable sectors. In response to these challenges, resource recovery has emerged as a transformative approach to waste management. This process involves extracting valuable materials, energy, or nutrients from waste streams, thereby converting waste into a resource rather than a burden.

1.1 End-of-Life (EOL) Solar Panels: An Emerging Waste Stream and Resource Opportunity:

With over 1.6 terawatts of solar capacity installed by 2024, the industry faces a growing waste crisis as early panels reach end-of-life. PV waste is projected to hit 8 million tons annually by 2030 and 78 million tons by 2050. Discarded panels contain valuable materials (glass, aluminium, silicon, silver, copper) and hazardous substances (lead, cadmium), posing serious environmental risks if landfilled or incinerated. Recycling offers a vital solution—recovering critical materials, reducing CO_2 emissions, and easing demand for mining. Yet less than 10% of panels are recycled due to challenges like energy-intensive processes, lack of standardization, and limited infrastructure.

1.2 Potential of Using Recycled Glass and Silica in Cementitious Materials

Cement blocks have long served as fundamental building material in global construction with several key advantages: high compressive strength, dimensional stability, fire resistance, and relatively low production costs. Hence considering the complete lifecycle of cement block construction, additional environmental impacts emerge from the extraction of natural aggregates (sand and gravel), which has led to severe ecological damage in riverine and coastal ecosystems worldwide. Among promising alternatives, recycled glass and silica-based materials offer both environmental and performance benefits. Finely ground waste glass (approx. 20 microns) (see Fig.1) can replace up to 20% of cement without compromising strength or durability. It acts as a pozzolan, improving workability, reducing permeability, and increasing resistance to freeze-thaw cycles and sulfate attack. Silica, particularly in nano or amorphous form (see Fig.2) enhances cement performance through its strong pozzolanic activity. It reacts with calcium hydroxide to form additional calcium silicate hydrate (C-S-H), the main strength-giving compound in concrete. Nano-silica improves early hydration, refines pore structure, and enhances strength, abrasion resistance, and chemical durability. Micro-silica and silica fume also contribute to reduced porosity and improved resistance to sulphate attack.

Fig 1: Glass Powder Extracted from Solar Panel by Crushing

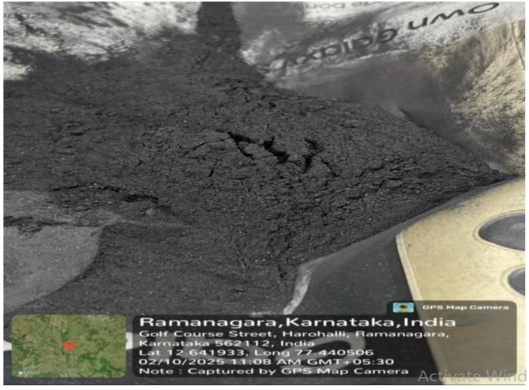

Fig. 2: Silica Power Extracted from Solar Panel

1.3 Study of blocks using end of life (EoL) solar panel

The main glass source in End of-life (EOL) solar panels is the cover glass that shields the silicon solar cells underneath. This glass, which normally accounts for 67–76% of the panel's overall weight, is mostly made of silica (silicon dioxide), which is first extracted from sand, one of the most plentiful natural resources on Earth. The silicon wafers that are incorporated into the solar cells are the source of silica. The main objectives of the study are 1) To characterize the physical (particle size, surface area) and chemical properties of recovered solar panel glass and silica. 2) To prepare concrete mix designs incorporating 12% of fine aggregate replacement and 12% of cement replacement of solar glass and silica to achieve enhanced performance characteristics. 3) Quantify and evaluate the compressive strength of concrete with combination of solar glass and silica proportions in relation to Indian Standards.

2.Materials and methodology

2.1 Materials

Source and Preparation of End-of-Life Solar Panels

Collection and Dismantling Process: This process involves a systematic and careful process to ensure safe handling and maximum material recovery. Collection begins with retrieving panels from various sources such as decommissioned solar farms, residential rooftops, commercial buildings, and storage sites. Once collected, the panels are moved to processing facilities where dismantling takes place. The dismantling process typically starts with the removal of the aluminum frame surrounding the panel, which can be easily separated and sent for recycling. Next, the junction box and attached electrical wiring, usually containing valuable copper, are detached. Some processes involve manual dismantling, they may be shredded whole, and the resulting material is later sorted mechanically or chemically. Proper dismantling is crucial not only for material recovery, including glass, silicon, and metals, but also for ensuring that hazardous substances are safely managed to prevent environmental harm.

Recovery and Processing of Solar Panel Glass (crushing, sieving): In the manual recovery of solar panel glass, the process starts by carefully dismantling the panels to remove the aluminum frame and electrical components like the junction box and wiring. Once these are removed, the glass layer is separated manually from the rest of the panel structure, which often includes silicon cells, encapsulant (such as EVA), and backing material. Manual extraction requires careful handling to avoid excessive breakage and to maximize the size and quality of the recovered glass sheets. After the glass is separated, any remaining adhesive or coating materials are gently scraped or cleaned off. If the extracted glass is already fragmented, it is further processed by manual crushing into smaller pieces as needed. Following crushing, sieving is done by hand or with simple mechanical sifters to separate clean glass fragments from other small impurities like bits of plastic or silicon.

Recovery and Processing of Solar Panel Silica: Here the process begins after the glass and other external components have been manually removed. Silica is primarily present within the solar cells in the form of purified silicon wafers. To recover this material, the remaining structure often a mix of silicon cells embedded in polymer layers—is carefully separated. If manual methods are used, mechanical tools or heating techniques may assist in loosening the encapsulant (usually EVA) that holds silicon in place. Once separated, the silicon pieces are collected and can be further cleaned by chemical or thermal treatments to remove any residual polymers.

Cement: Cement is fundamentally a binder, a substance that sets and hardens independently, and can bind other materials together. When mixed with water, it forms a paste that subsequently hardens through a chemical process known as hydration. This hardened cement paste is strong and durable, making cement a crucial ingredient in the production of concrete and mortar. In this project 53 grade cement is used.

Aggregate: These are inert granular materials such as sand, gravel, or crushed stone that, along with water and Portland cement, are an essential ingredient in concrete. There are two types of aggregate: Fine aggregate and coarse aggregate. Fine aggregates are granular materials that are smaller than 4.75 mm in size and are essential components in concrete and mortar mixes. They primarily consist of natural sand, crushed stone sand. Coarse aggregates typically larger than 4.75mm in diameter which are predominant types of crushed stone employed include granite, limestone, and trap rock.

Silica: Also known as silicon dioxide (SiO_2), is a by-product of the production of silicon and ferrosilicon alloys, and its fine particle size and high surface area contribute to its pozzolanic behavior, meaning it reacts with calcium hydroxide in cement to form additional calcium silicate hydrate (CSH), which improves concrete's strength and durability.

Glass: It is a non-crystalline, amorphous solid material that is commonly composed of silica (silicon dioxide, SiO_2) along with other materials such as sodium carbonate, calcium oxide, and other oxides that modify its properties. In concrete applications, glass is typically used in two forms: Aggregate or pozzolanic material and Glass powder. Crushed glass can be used as a partial replacement for fine aggregates like sand whereas glass powder can be used as supplementary cementitious material.

2.2 Mix Design

Development of different mix proportions

To investigate the potential of utilizing End-of-Life (EOL) solar panel waste in M25 grade concrete, a controlled set of mix proportions was meticulously developed. A standard control mix, formulated according to IS 10262:2019 and IS 456:2000, served as the benchmark. This mix targeted a mean strength of 31.6 N/mm² using OPC, natural sand, and coarse aggregate with a water-cement ratio of 0.45. The first strategy involved substituting a portion of the cement with fine silica powder derived from crushed solar panels. For replacement level, the weight of cement was reduced, and an equal weight of silica was added, while maintaining a consistent water-to-binder ratio. The second strategy focused on replacing a fraction of the natural sand with crushed and graded glass particles from solar panels. Here, the weight of sand was reduced, and an equivalent weight of glass was introduced, keeping the cement, water, and coarse aggregate quantities consistent with the control mix. materials, ensured comparable solid volumes across all mixes. This systematic approach allowed for a direct evaluation of how the incorporation of solar panel silica and glass at certain percentages influenced the workability and, crucially, the 28-day compressive strength of the resulting M25 grade concrete.

Table 1: Components of Mix Proportion

SL. No.	Components	Concrete Blocks
1	Cement	OPC 53
2	Ratio	1:1:2
3	Block dimensions (mm)	150 x 150 x 150
4	Block volume (m³)	0.003375
5	Number of blocks	10
6	Total volume (m³)	0.03375
7	Shrinkage factor	52 %
8	Total Dry Mix Volume (m³)	0.0513

Table 2: Mix Proportion with 12% Fine Aggregate (Sand) Replacement by Solar Panel Glass in Gravel-Based Blocks

Percentage variation (%)	Material quantity (kg)				Water cement ratio	Quantity of water (ml)
	Cement	Sand	Glass	Gravel		
12	18.6	20.32	3.85	41	0.45	8370

Percentage variation (%)	Material quantity (kg)				Water cement ratio	Quantity of water (ml)
	Cement	Sand	Silica	Gravel		
12	16.36	23.085	3.68	41.04	0.45	7362

Table 3: Mix Proportion with 12% Cement Replacement by Solar Panel Silica in Gravel-Based Block

Table 4: Mix Designs with 12% Combined Replacement: Glass for Sand and Silica for Cement in Concrete Blocks

Percentage variation (%)	Material quantity (kg)					Water cement ratio	Quantity of water (ml)
	Cement	Sand	Silica	Glass	Gravel		
12	16.38	20.32	3.68	3.85	41.04	0.45	7371

2.3. Mixing and Casting:

Mixing procedure: To begin, materials should be measured based on the mix design, then start the process with dry mixing by combining cement and sand in a mixing container, ensuring the mixture is blended thoroughly until a uniform colour is achieved without visible streaks. Water should then be added slowly while mixing continuously to reach a stiff but mouldable consistency, careful not to add too much, as overly wet mixes can cause small blocks to lose their shape. Check the workability by pressing the mix; it should hold its form like damp clay. Optional additives may be used to enhance performance for example, a few drops of plasticizer can improve workability, while microfibers can be added for better crack resistance if available. Finally, the mixture should be stirred for 3 to 5 minutes until it becomes homogenous.

Casting: Moulds should be rigid, non-absorbent and leak proof, a thin layer of oil is applied this prevents concrete adhesion, then moulds are assembled tightly to prevent leakage of concrete slurry. The moulds are filled with concrete in 3 layers and each layer compacted using tamping road or vibration table and then the top surface is levelled with trowel.

Curing: De-moulding is done after initial Curing for 24hours after casting with laboratory temperature of 27°C ± 2°C. After de-molding, the specimens are placed in water curing tank for 7 days, 14 days and 28 days. The cast specimens were placed fully submerged in curing tank containing fresh water at the laboratory temperature of 27°C ± 2°C.

3. Testing methods

3.1 *Testing at Specified Ages*: Removed specimen from water, wipe surface moisture, and measure dimensions. Then placed the block in the Compression testing machine (CTM), ensuring even load distribution. Load is applied continuously at 140 kg/cm^2/min (≈0.23 MPa/sec for 150mm blocks). Recorded the maximum load (P) at failure. Testing of concrete block is done for 7 days, 14 days and 28 days. Then the compressive strength is calculated for all the specimens and results are drawn compared to all the combinations. Block preparation, curing at 27 ± 2°C, and testing methodologies conform to IS 516:1959 standards.

4. Results and Discussions:

4.1 Characterization of Recovered Solar Panel Glass and Silica

Physical Properties: XRD test (X- Ray Diffraction)

XRD (X-ray Diffraction) analysis of silica extracted from solar panel waste reveals high-purity material, often confirming the conversion of complex solar module components into refined **amorphous or crystalline SiO_2**. The analysis is critical for validating the removal of contaminants like Aluminum (Al) and Silver (Ag). XRD, shows that extracted silica can reach high purity levels (above 99% SiO_2). XRD patterns demonstrate the reduction or disappearance of impurity peaks (fig .3)

Table 5: XRD test of silica crystals extracted from solar panel

Element	Weight % Average of 3
Al	0.63
Si	99.0
Ag	0.37

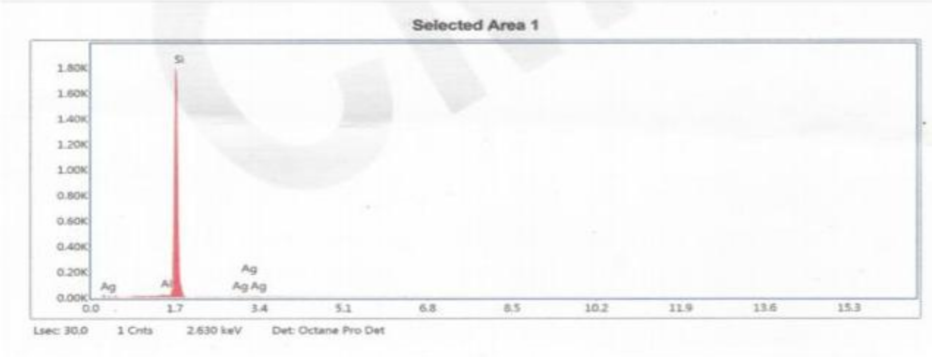

Fig 3. XRD (X-ray Diffraction) analysis of silica

Specific Gravity: The ratio of the density of glass to the density of water is known as specific gravity. The specific gravity for recovered solar panel glass is around 2.5 to 2.6. This measurement helps confirm material composition and detect contamination, such polymer residues

Bulk Density: The mass of crushed glass per unit volume, considering void spaces between particles, defines its bulk density. This property is measured by gently pouring the glass fragments into a container of known volume and weighing. Bulk density for crushed solar panel glass usually ranges between 1.2 to 1.6 g/cm^3, depending on particle size. Understanding bulk density is important for transport, storage, and feeding into recycling or manufacturing equipment.

Chemical Properties: XRF Analysis Typical Major Elements Found:

- Silicon (Si) – Present as silicon dioxide, the primary component of glass (~65-75%).
- Sodium (Na) – As sodium oxide (Na_2O), added for glass forming (~12-15%).
- Calcium (Ca) – As calcium oxide (CaO), provides strength (~8-10%).
- Magnesium (Mg) – As magnesium oxide (MgO), enhances durability (~2-5%).
- Aluminum (Al) – As aluminum oxide (Al_2O_3), improves chemical resistance (~1-3%).

Possible Minor or Trace Elements:

- Iron (Fe) – Can appear as impurities or for coloring purposes.
- Tin (Sn) – May be present if the glass was treated with a tin-based coating.
- Lead (Pb), Cadmium (Cd) – Trace amounts may be detected in older panels

4.2 Compressive Strength of Concrete with Solar Panel Glass Replacement

The compressive strength development of the M25 grade concrete incorporating 12% partial replacement of fine aggregate with glass was evaluated at curing ages of 7, 14, and 28 days. The compressive strength values obtained from the testing of specimens at these ages are graphically presented as follows:

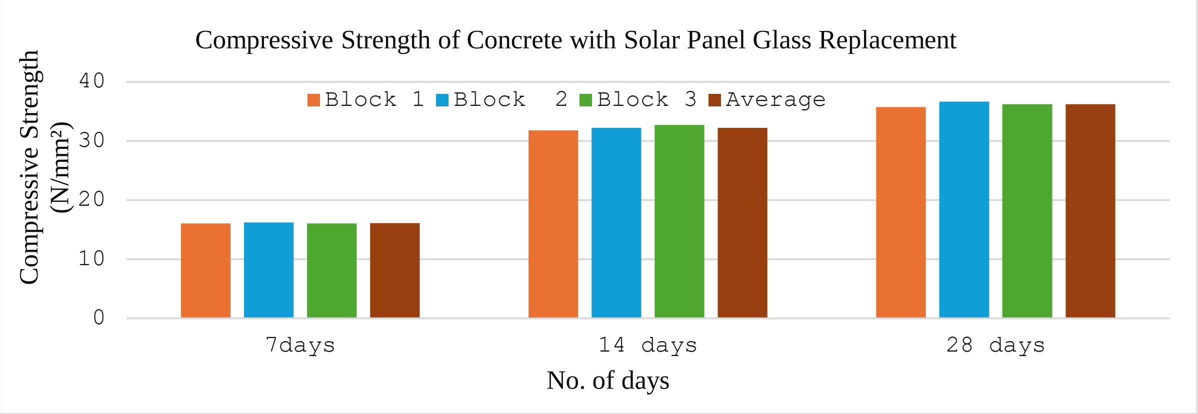

Fig.4: Graphical representation of compressive strength of concrete with solar panel glass replacement

Table 6: The average compressive strength values obtained from the testing of specimens at these ages

No. of days	7 days	14 days	28 days

Average compressive strength (N/mm^2)	16.11	32.24	36.223

At 7 days, the modified concrete achieved 16.113 N/mm² (44.5% of 28-day strength), below the typical 60-70% for conventional mixes, suggesting slower early strength gain. By 14 days, it reached 32.24 N/mm² (89% of 28-day strength), aligning with the standard 85-95% range, indicating recovery. The 28-day strength of 36.223 N/mm² suggests good-quality concrete. The trend shows delayed early strength but strong later development. The achieved strength is 36.223 N/mm², significantly exceeding the M25 requirement of 25 N/mm² by approximately 45%, indicating robust ultimate strength development. The modified mix successfully meets all strength criteria for M25 concrete per IS 456:2000, with substantial over-performance at 28 days. While early strength gain is marginally slower, it remains within acceptable limits for quality control.

4.3 Compressive Strength of Concrete with Solar Panel Silica Replacement

The compressive strength of concrete is a fundamental mechanical property that dictates its suitability for structural applications. This section analyses the compressive strength development of the M25 grade concrete mix incorporating a 12% partial replacement of cement with silica powder, based on tests conducted at 7, 14, and 28 days of standard curing. The compressive strength values obtained from the testing of specimens at these ages are graphically presented as follows

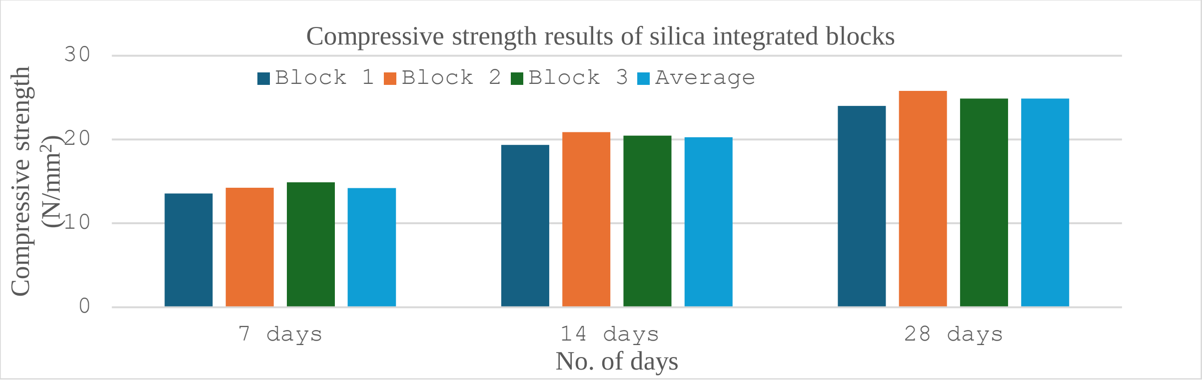

Fig.5: Graphical Representation of compressive strength results of silica integrated blocks

Table 7: The average compressive strength values obtained from the testing of specimens at these ages

No. of days	7 days	14 days	28 days
Average compressive strength (N/mm^2)	14.22	20.226	24.89

The experimental results demonstrate the expected progressive strength gain with curing time, characteristic of cement hydration, with significant early strength development between 7 days (14.22 N/mm²) and 14 days (20.226 N/mm²), followed by a slower but continued increase to 24.89 N/mm² at 28 days. While this trend reflects typical hydration behavior, the 28-day strength marginally falls short of the M25 grade requirement (25 N/mm² as per IS 456:2000). The inclusion of 12% silica powder as a cement replacement introduces pozzolanic activity, where silica reacts with calcium hydroxide to form additional C-S-H gel, often enhancing strength and durability particularly at later ages beyond 28 days. However, within the standard testing period, the mix did not conclusively achieve the target strength, suggesting that the chosen replacement level or mix proportions may require optimization. Early-age results (7- and 14-day strengths) indicate adequate hydration progression, but the slight 28-day deficit highlights the need for potential adjustments, such as modified silica content, enhanced curing, or supplementary cementitious materials. Further testing with larger sample sizes and extended curing periods (e.g., 56 or 90 days) would clarify the long-term pozzolanic benefits and statistical compliance with IS 456 acceptance criteria. Until then, this mix design warrants caution for strict M25 applications unless supplemented with additional strength validation.

4.4 Compressive Strength of Concrete with Combined Solar Panel Glass and Silica Replacement

The compressive strength results for the M25 grade concrete mix incorporating a dual partial replacement strategy: 12% silica powder as a partial replacement for cement and 12% glass powder as a partial replacement for fine aggregate. Evaluating the compressive strength development of concrete with combined supplementary cementitious materials and recycled aggregates is essential for understanding their synergistic effects on mechanical performance. Tests were conducted at curing ages of 7, 14, and 28 days under standard curing conditions. The average compressive strength values obtained from the testing of multiple specimens at each curing age are as follows:

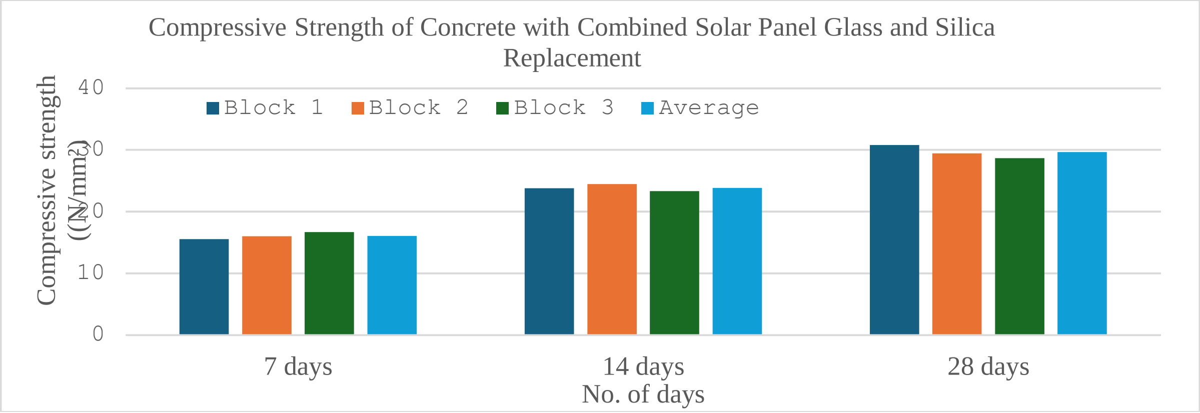

Fig.6: Graphical representation compressive strength of concrete with combined solar panel glass and silica replacement

Table 8: The average compressive strength values obtained from the testing of specimens at these ages

No. of days	7 days	14 days	28 days
Average compressive strength (N/mm^2)	16.67	23.85	29.63

The concrete with 12% silica powder (cement replacement) and 12% glass powder (fine aggregate replacement) achieved a 28-day compressive strength of 29.63 N/mm², significantly exceeding the M25 grade requirement of 25 N/mm² per IS 456:2000. The strength progression showed healthy development - 16.67 N/mm² at 7 days and 23.85 N/mm² at 14 days - indicating effective early hydration despite the replacements. The superior final strength demonstrates successful synergy between the materials: silica powder's pozzolanic reactivity complemented glass powder's micro-filler effect, together compensating for reduced cement content. These results validate this dual-replacement approach as technically viable for producing M25+ concrete while incorporating sustainable alternative materials. The 18.5% strength margin provides a comfortable performance buffer, suggesting good potential for practical application in structural concrete.

4.5 Comparison with Single Material Replacement and Control Mix

All mixes were designed for M25 grade concrete, which requires a characteristic compressive strength of 25 N/mm^2 at 28 days as per IS 456:2000. Here's a summary of the average compressive strength results for each mix at different curing ages:

Table 9: Comparative Average Compressive Strength (N/mm^2)

Mix Composition	7 days	14 days	28 days
12% Glass (Fine Aggregate Replacement)	16.113	32.24	36.223
12% Silica Powder (Cement Replacement)	14.22	20.226	24.89
12% Silica (Cement) + 12% Glass (Fine Aggregate) Replacement	16.67	23.85	29.63
Typical Conventional M25 Concrete (Reference)	15-17.5	21.25- 23.75	25

For M25 concrete with 12% glass powder (FA) and 12% silica powder (cement) reveal that the 28-day strength for the glass FA mix was 36.22 MPa, exceeding the M25 requirement by 45%. The silica-only mix achieved 24.89 MPa, slightly below the 25 MPa target, while the combined mix of 12% silica and 12% glass reached 29.63 MPa, comfortably surpassing the requirement. The strength development patterns showed that the glass FA mix demonstrated rapid strength gain from 7 to 14 days (16.11–32.24 MPa), reaching the highest final strength, while the silica mix had a slower early strength development (14.22 MPa at 7 days) but almost met the M25 target at 28 days. The combined mix showed balanced strength development (16.67–29.63 MPa). Glass powder enhanced strength through a micro-filler effect and potential pozzolanic activity, while silica contributed to later-age strength, and glass supported early development. Both the 12% glass FA replacement and the combined 12% silica+12% glass mixes successfully produced M25+ concrete, with glass FA showing superior strength performance. The silica-only mix nearly missed the 28-day target, indicating the need for extended curing to fully realize pozzolanic benefits. The results validate the use of these sustainable alternatives for concrete applications, though comparison with control mixes under identical conditions is recommended for a complete assessment.

5. Conclusions

This research effectively explores the use of End-of-Life (EOL) solar panel waste to enhance concrete block production, contributing to sustainable waste management within the construction sector. The key findings are:

Material Suitability: The processed glass (45-75µm, 2.4-2.5 specific gravity) and silica (high amorphous content, 15,000-20,000 cm^2/g surface area) from EOL solar panels are viable concrete components.

Strength Enhancement: By replacing 12% of fine aggregate with glass significantly increased compressive strength (e.g., 36.223 N/mm^2 at 28 days), outperforming the M25 target. 12% silica replacement showed good strength development, though slightly below M25 at 28 days (24.89 N/mm^2), indicating potential for optimization. Combining 12% glass and 12% silica achieved excellent results (29.63 N/mm^2 at 28 days), demonstrating a positive interaction.

The research confirms that using recycled solar panel waste in concrete blocks is a viable strategy. This approach reduces environmental burden by decreasing both landfill waste and the CO2 emissions linked to traditional cement production. These results validate the technical viability of using sustainable recycled materials in structural concrete, though further durability studies (IS 516-Part 5), field trials, and economic analysis are recommended for commercial implementation.

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