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RESEARCH PAPER

Lightweight concrete from solar waste: a sustainable solution

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Abstract
The solar photovoltaic (PV) panel waste has high potential to damage the earth and its resources if not carefully disposed. In this research, cement and coarse aggregate are partially replaced with functional layers (silicon wafer, ethylene vinyl acetate sheet, busbars, fingers) and glass of solar panels in M25 grade concrete. This method demonstrates that the recycling process can replace 11.69 billion tonnes of cement and 98.46 billion tonnes of gravel with materials derived from solar panels. The concretes manufactured have densities of 1860.91 kg/m^3 and 1943.79 kg/m^3, categorizing them as lightweight concretes. SEM and TEM analysis shows good hydration and bonding in the concrete. Brunauer–Emmett–Teller analysis demonstrates lightweight concrete has a surface area of 12.524 m^2/g and 11.514 m^2/g against 6.910 m^2/g for conventional concrete. The lightweight concrete has thermal conductivities of 0.106 W/mK and 0.115 W/mK, compared to 0.295 W/mK for conventional concrete. After being cured in water and HCl acid, concrete cubes were subject to a compression test and they attained the designed strength. This research corresponds with the UN Sustainable Development Goals (7, 9, 12, 13, 15) by providing a sustainable and efficient strategy for solar waste management.

Keywords Lightweight concrete · Solar PV recycling · BET analysis · Filler concrete · Carbon emission · Resource management

Introduction

Recycling solar panels is of the utmost importance to reduce pollution, conserve resources, and lessen environmental impact. Recycling materials such as toughened glass and other layers of solar panels in cement matrices reduces the demand for extraction of raw materials used in concrete and conserves natural resources. Through the diversion of end-of-life panels from landfills, incineration, chemical processing, dumping in water or any other mismanagement, recycling them in concrete serves to mitigate large-scale environmental hazards and also immobilizes the toxic solar waste into concrete as a perpetual solution (Kumar and Sundararaj 2025). In addition, recycling contributes to energy conservation and emission reduction. By ensuring the secure disposal of hazardous substances discovered in panels through proper recycling, ecosystems and human health are safeguarded (Sharma et al. 2021). The adoption of solar panel recycling practices in the renewable energy sector fosters economic opportunities, regulatory compliance, circular economy principles, and long-term sustainability (Gao et al. 2024).

Lightweight concrete with higher porosity is ideal for structural engineering applications that require weight reduction. Examples include marine structures, high-rise skyscrapers, and bridges. Lightweight concrete is strong and durable despite its decreased density (Bian et al. 2024). Porosity can also improve fire resistance and acoustics. Air contained in concrete inhibits heat transfer, allowing time for building evacuation and fire suppression in an emergency (Tang et al. 2024).

The 3D analysis of concrete was conducted using BET, MIP, and SEM (Tarhan and Şahin 2024). Results showed that air-entraining admixture (AEA) increased cemented matrix pore volume and size. Mechanical and durability testing showed that 0.1% AEA is the most optimum. The

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research by Karadumpa and Pancharathi (2024) examines five distinct cement manufacturing facilities situated in the northern, southern, eastern, western, and central regions of India to evaluate the energy dissipation and carbon dioxide emissions associated with the manufacture of ordinary Portland cement (OPC). The CO_2 emission intensity for OPC ranges from 893 to 940 kg per tonne over five distinct zones. The analysis by Barbhuiya et al. (2024) offers an extensive examination of the decarbonisation of cement and concrete manufacturing, focusing on techniques, technology, regulatory considerations, case studies, economic ramifications, problems, and future suggestions.

A life-cycle environmental study by Daniela-Abigail et al. (2022) indicates that these consequences may be mitigated by photovoltaic recycling, resulting in a significant reduction in human toxicity and freshwater ecotoxicity by around 78%. Life-cycle cost evaluation has shown that the levelized cost of energy with photovoltaic recycling may be around 2% lower than in scenarios without photovoltaic recycling. Policy frameworks and recycling strategies for crystalline, thin film, organic, gallium arsenide, perovskite, and dye-sensitive solar panels were examined by Ndalloka et al. (2024). Sustainable materials management was developed by researching retired solar panel supplies by Jung et al. (2016) and recovered 80%, 79%, and 90% Si, Cu, and Ag, and 93% Pb. Wongnaree et al. (2020) purified reduced Ag powder and electrolytically refined Ag to 99.7% and 99.99%.

Shang et al. (2024) investigated whether biomass ash and slug waste could produce artificial aggregate (AA). Response surface methods and experimental tests were used to find and optimize palletisation parameters. Resende et al. (2024) replaced conventional aggregate with polyethylene terephthalate. Hamada et al. (2024) examines prior research data from 2020 to 2024 to see if plastic waste can be used in cement concrete components. Plastic polymers were used as concrete reinforcement in a similar study by Al-Alusi et al. (2024). Hou et al. (2024) describes how to make porous concrete with 15%, 20%, and 25% porosity. For each goal porosity, 10 water–cement ratios from 0.2 to 0.4 were designed. After curing, the samples were tested for porosity, permeability, and compressive strength.

A circular economy strategy also involves using blockchain technology to track solar panel disposal and introducing Recycling Coin (RC-coin) to encourage recycling (Chowdhury et al. 2024). Solar panels should be recycled to prevent the discharge of harmful chemicals that can harm humans and the environment. Thus, a solar panel trash recovery and reuse process is essential (Zele et al. 2024). Vinayagamoorthi et al. (2024) summarized photovoltaic technology classification and global PV waste management methods.

The significance of material porosity in the manufacture of lightweight concrete and its impact on concrete quality were recognized. Consequently, we formulated the M25 grade concrete and conducted multiple experiments with the objective of minimizing solar panel waste and managing the environmental consequences associated with both the solar panel waste mismanagement and the manufacturing of conventional cement and coarse aggregate. Consequently, we have developed lightweight concrete and filler concrete that possess excellent thermal qualities, making them suitable for a wide range of practical uses. So, from the study, the following objectives were framed: "Resource conservation through sustainable recycling of solar PV panels" and "to study the porosity, strength, thermal properties, and water and acid resistance of the concrete developed using the recycled solar PV panels."

Methodology

By extrapolating laboratory-scale results to global contexts, such as the prediction of incorporating solar waste into billions of tonnes of concrete, this study sought to highlight the increased sustainability potential of recycling. Through a scenario-based approach, the goal is to demonstrate how end-of-life photovoltaic panels can greatly improve a circular economy framework by diverting e-waste from landfills and reducing reliance on virgin building materials.

The integration of various solar photovoltaic panel components into concrete matrices is the primary focus of this research. A partial amount of cement has been replaced with functional layer powder (silicon wafer, EVA sheet, bus-bar, fingers), and the coarse aggregate has been replaced with toughened glass pieces that were obtained from solar panels, as shown in Fig. 1. This investigation utilized a total of 10 solar panels, each rated at 325 W. The panels weighed around 21 kg each and were then prepared for use as substitutes in concrete.

The panel's layers were ground with an angle grinder, serving as a substitute for cement, and the glass was chopped into 20 mm pieces to replace traditional 20 mm gravel. Prior to their incorporation into concrete, the properties of the components were meticulously compared with those of the conventional materials, and the analysis is documented in the results section. The mass of materials extracted from each panel during the process, along with data from the production facility, has been utilized to calculate the total materials that can be obtainable from existing solar panels across the world. The computation presented in the results section has been compared to the possible savings of virgin materials and energy resources in the manufacturing process of

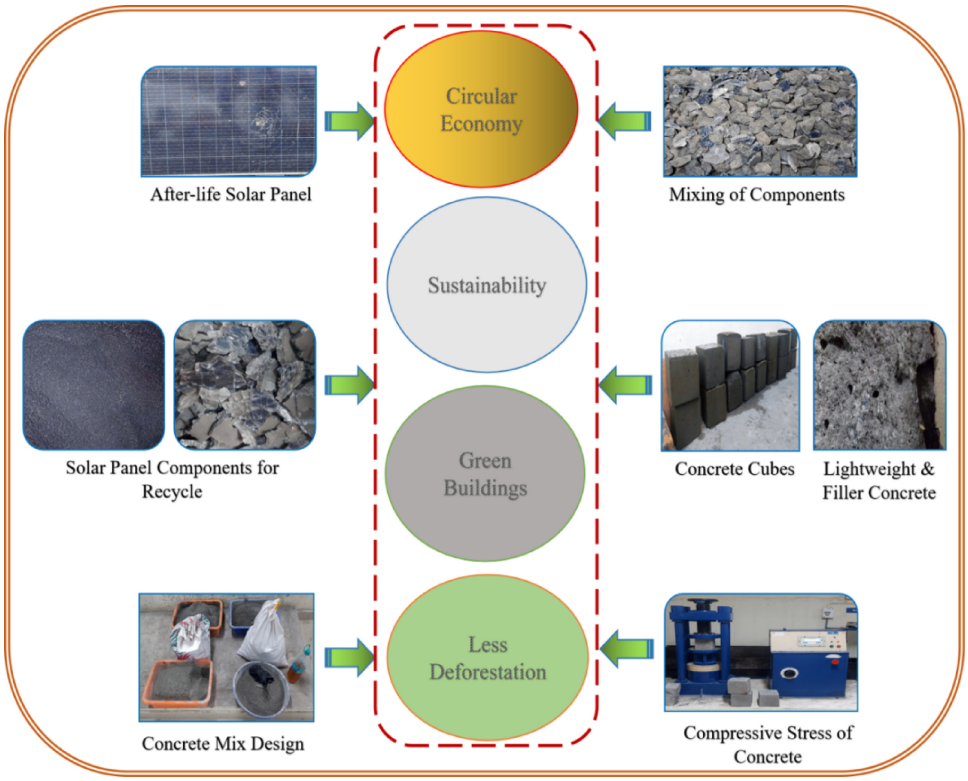


Fig. 1 Recycling solar PV panel in cement matrices (Raysus Custom Concrete Solutions Private Limited 2025)

raw materials for cement and coarse aggregate through the utilization of the recycled materials.

This technology is cost-effective and efficient, requiring minimal processing that is entirely mechanical, devoid of specialized chemicals or apparatus for panel processing. Utilizing these components in concrete for green buildings can mitigate deforestation, foster a circular economy, and prevent the interaction of hazardous substances with terrestrial, aquatic, and atmospheric resources.

After the materials have been processed, this research has led to the development of four distinct types of concrete: (a) Conventional concrete (M1); (b) Concrete in which functional layer powder and toughened glass have been partially incorporated in place of cement up to 10% and coarse aggregate up to 10% (M2); (c) Concrete in which 10% cement was replaced with functional layers (M3); (d) Concrete in which toughened glass fragments from solar panels have been utilized as partial replacement of coarse aggregate up to 10% (M4).

Concrete mix designs were developed in compliance with IS 10262:2019 (BIS 2019) for M25 grade concrete. The mixing technique was conducted methodically with a pan mixer, ensuring comprehensive dispersion of dry components prior to the incorporation of water and superplasticizers. The mixing quality was visually evaluated to avert clumping or segregation. The mixture ratio was computed as follows: 1:1.53:2.59 for cement, fine aggregate, and coarse aggregate, and the concrete design is shown in Table 1.

A set of 72 cubes with dimensions of 150 mm × 150 mm × 150 mm were manufactured, subsequently positioned on a concrete vibrator table to compact and consolidate the mixture. The concrete cubes was allowed to set for 24 h within the moulds, followed by immersion in water at 27 ± 2 °C for curing duration of 7, 14, and 28 days, along with additional periods of 7, 14, and 28 days for HCl acid curing. To guarantee the reliability and reproducibility of results, three cubes of each kind were fabricated for the compressive strength test in accordance with IS 516:2021 (BIS 2021).

A series of experiments were performed on the concrete cubes, including comparison with conventional materials, SEM, TEM, BET, water and acid curing, thermal conductivity, and compression tests. Upon mixing and pouring the concrete containing cement replacement into the moulds, it was noted that the M2 and M3 concrete cubes exhibited a bulging action of up to 4 cm. Protrusion and fracturing of bubbles were observed on the uppermost stratum of the moulds. This reaction was observed from the moment the concrete was poured into the mould until it began to set, for almost 40 min. As soon as the concrete reaches the desired setting, both the concrete expansion and the chemical reaction that produces the bubbles cease.

The SEM and TEM analysis were performed using FEI Quanta 200 and JEM 2100 Plus, and the porosity test was necessitated in order to ascertain the true capabilities of M2 and M3 concrete in practical implementations across industries, in light of its expansion behaviours. Thus, the surface

Table 1 Concrete mix design

S. no.	Mix ID	Cement (kg/m^3)	Fine aggregate (kg/m^3)	Coarse aggregate (kg/m^3)	Water (kg/m^3)	w/c ratio	Cement replacement (kg/m^3)	Volume replacement (Cement)	Coarse aggregate replacement (kg/m^3)	Volume replacement (coarse aggregate)	Super plasticizer (kg/m^3)
1	M1	433.75	620.33	1123.63	147.87	0.375	0	0	0	0	4.37
2	M2	390.38	620.33	1067.45	147.87	0.375	43.37	10%	112.37	10%	4.37
3	M3	390.38	620.33	1123.63	147.87	0.375	43.37	10%	0	0	4.37
4	M4	433.75	620.33	1011.26	147.87	0.375	0	0	112.37	10%	4.37

area and porosity distribution of the specified concrete were determined via the Brunauer–Emmett–Teller (BET Porosity Analysis) test using Quantachrome Autosorb-iQ-MP/MP-XR for the M1, M2, and M3 concretes.

Figure 2a illustrates the expansion taking place in the mould after the mixes were poured into the mould, and Fig. 2b reflects the expanded part of concrete within the mould after the concrete is set.

Consequently, due to the concrete's very porous characteristics, it is essential to examine another property of the material: its thermal conductivity, using the METER KD2 PRO Thermal Property Analyzer. After all the tests were performed and evaluated, including the weighing of the cubes, compression test is performed by using VIION Universal Testing Machine 2000 kN on 36 cubes after 28 days of water curing and the remaining cubes after another 28 days of curing in HCl acid.

Results and discussion

The formulated concretes M2 and M3 demonstrates densities of 1860.91 kg/m^3 and 1943.79 kg/m^3, markedly lower than that of traditional concrete (2401.22 kg/m^3). The M4 concrete has a density of 2305.11 kg/m^3. These values are consistent with the upper limit established by international standards, including ACI 213R (ACI Committee 213 2014) and IS 456:2000, for lightweight concrete. The increased specific surface areas (12.524 and 11.514 m^2/g vs. 6.910 m^2/g) signify improved porosity and diminished mass per unit volume, so reinforcing its designation as lightweight concrete. The results derived from the various analysis conducted on the concretes are as follows:

Resource conservation

The total mass of materials from solar panel is calculated based on their current installed capacity around the globe and the top 5 countries, based on the data from the International Renewable Energy Agency (https://www.irena.org/Data/View-data-by-topic/Capacity-and-Generation/Country-Rankings), in Table 2. It is calculated that the mass of the silicon wafer, fingers, EVA sheet and bus bar is 11.69 billion tonnes. These are the most toxic components of a solar PV panel and were found to be a suitable replacement for cement when finely crushed and can replace cement up to 10% in a concrete design. Further calculations based on the data from the International Energy Agency (https://www.iea.org/energy-system/industry/cement) proved that the production of 11.69 billion tonnes of cement requires significant resource utilization and energy expenditure. To produce this amount of cement, roughly 16.37 billion tonnes of

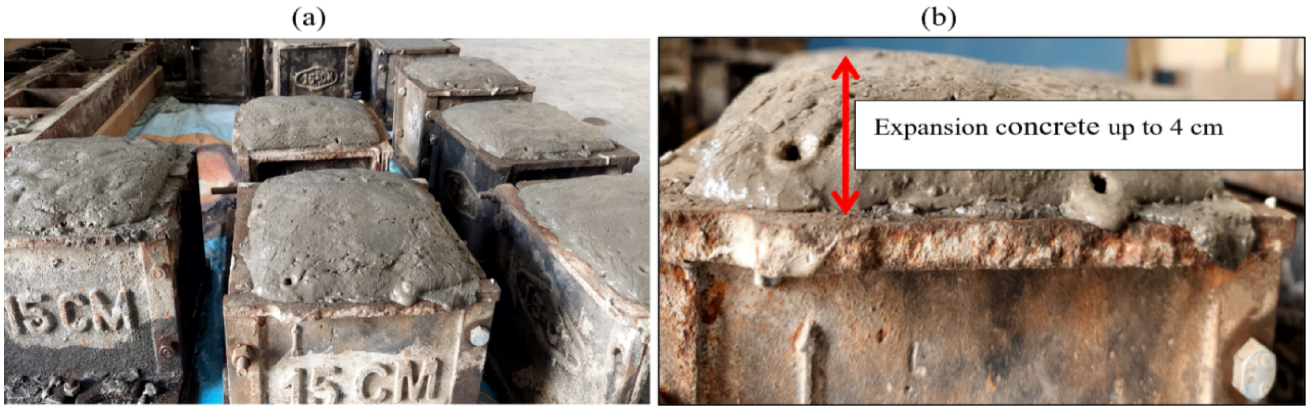


Fig. 2 **a** Expansion of the concrete in the initial stages of setting; **b** Expanded part of the concrete after setting

Table 2 Mass of components of PV panel based on the current installation across the world and the top five countries

Component	Mass in kg (325 W PV panel with 72 cells)	World (kg)	China (kg)	USA (kg)	Japan (kg)	Germany (kg)	India (kg)
Glass	16	9.84615E+11	6.00537E+11	1.37063E+11	85,728,480,000	80,481,472,000	71,184,240,000
Aluminium frame	3	1.84615E+11	1.12601E+11	25,699,383,000	16,074,090,000	15,090,276,000	13,347,045,000
Silicon wafer	1.5	92,307,691,500	56,300,307,000	12,849,691,500	8,037,045,000	7,545,138,000	6,673,522,500
Fingers and bus bars	0.3	18,461,538,300	11,260,061,400	2,569,938,300	1,607,409,000	1,509,027,600	1,334,704,500
Junction box	0.1	6,153,846,100	3,753,353,800	856,646,100	535,803,000	503,009,200	444,901,500
EVA sheet	0.1	6,153,846,100	3,753,353,800	856,646,100	535,803,000	503,009,200	444,901,500
Total mass	21	1.29231E+12	7.88204E+11	1.79896E+11	1.12519E+11	1.05632E+11	93,429,315,000

limestone, 1.75 billion tonnes of clay, 0.37 billion tonnes of silica sand, 0.05 billion tonnes of iron ore, and 0.23 billion tonnes of gypsum are necessary.

The energy required for the manufacturing process totals around 46,760,000 TJ (3.6 GJ/t of clinker). The manufacture of this quantity of cement generates substantial CO_2 emissions, which is 0.85 kg of CO_2, resulting in total emissions of around 10.52 billion tonnes of CO_2. The substantial resource and energy use, together with elevated CO_2 emissions as per the data from Integrated Pollution Prevention and Control of the European Union (https://eippcb.jrc.ec.europa.eu/sites/default/files/2020-03/superseded_clm_bref_1201.pdf), emphasizes the environmental repercussions of conventional cement manufacturing, illustrating the potential advantages of using alternative resources.

Similarly, the toughened glass of the solar PV panel, which is about 98.46 billion tonnes, can replace the conventional coarse aggregate up to 10% in the concrete design. The production of gravel for coarse aggregate also entails considerable resource utilization, expenses and deforestation, just like processing the raw materials to manufacture cement.

Sustainable development strategies employing cement matrices can effectively mitigate pollution by encapsulating hazardous substances and diminishing anthropogenic environmental impact, ensuring that the shift to renewable energy does not jeopardize human health and ecological equilibrium (SDGs 3, 7, 9, 11, 12, 13, 15, and 17). Moreover, the release of hazardous substances, including chromium, lead, and cadmium into the environment, can be mitigated by a recycling process as per the Photovoltaic Power System Programme by the International Energy Agency (https://iea-pvps.org/wp-content/uploads/2024/06/IEA-PVPS-T12-28-2024-Report-PV-Recycling-LCI_EPRI.pdf). The need for creating a circular economy for solar photovoltaic systems has been highlighted by the International Renewable Energy Agency (IRENA) (https://www.irena.org/Energy-Transition/Policy/Circular-economy) and the International Energy Agency (IEA) (https://iea-pvps.org/wp-content/uploads/2024/03/IEA-PVPS-T12-02-2024-FACT-SHEET-Circular-Economy.pdf).

Material analysis

This analysis emphasizes the significant potential of these waste materials in modern construction, providing both environmental and structural benefits. The elevated silica concentration in PV waste positively affects hydration processes, leading to improved microstructure and greater bonding within the concrete matrix. This approach may yield an

optimal combination of strength, durability, and workability by thorough optimization of the mix design and the incorporation of additives such as superplasticizers. Although PV layer waste cannot fully replace conventional cement due to its limited inherent cementitious properties, it functions effectively as a secondary binder, rendering it an excellent supplementary material for sustainable construction.

Replacing conventional gravel with waste from solar PV tempered glass presents a comparably compelling opportunity. This material possesses density and strength properties similar to natural aggregates, validating its suitability as a structural component in concrete. The impermeable properties of PV glass waste substantially enhance the durability of concrete by preventing water absorption, which is essential for long-term structural integrity. The diminutive particle size and exceptional mechanical stability improve workability, aiding in the mixing and pouring of the concrete. Table 3 gives a comprehensive comparison of the attributes of conventional materials and their replacement counterparts.

SEM and TEM analysis of the functional layer and the concretes

The SEM analysis of the functional layers of the solar panel (Fig. 3a) indicates a composition mostly of tin (Sn) and lead (Pb), with weight percentages of 57.28% and 35.78%, respectively. The elevated levels of lead generate environmental and safety issues owing to its hazardous characteristics, necessitating cautious consideration in any recycling or reuse endeavours. The examination reveals tiny amounts of carbon (2.04 wt%) and oxygen (4.45 wt%), perhaps resulting from surface pollution, organic molecules, or oxides such as SnO_2 or PbO. Aluminium is found in trace quantities (0.46 wt%), perhaps originating from the non-reflective coating on the solar wafer.

The TEM investigation of the concrete samples (Fig. 3b–e) indicates a complex and heterogeneous nano-structure mostly composed of silicate and alumino-silicate phases. The elemental analysis reveals elevated levels of silicon and oxygen, suggesting the existence of silicate-based compounds linked to calcium-silicate-hydrate (C-S-H), which constitutes the principal binding phase in hydrated cement. The calcium is the major component of the mixture, followed by silicon and aluminium, which is found in significant amounts, indicating the presence of alumino-silicate phases, while potassium and iron are presumably derived from trace mineral elements or impurities.

It is evident that the conventional concrete M1 (Fig. 3e) and the concretes using solar panel waste (Fig. 3b–d) exhibit considerable similarity in composition and performance. This analysis demonstrates that the concrete composed of solar panel waste, which is highly toxic, effectively encapsulates the toxicity due to the predominance of conventional materials in the mixture and the chemical reactions occurring during the curing process, rendering this method a safe means of disposing of toxic waste.

Porosity analysis using BET analysis

The chemical reactions occurring during the expansion of concrete (M2 and M3) were investigated and comprehended. A variety of hydrated calcium aluminate phases are formed when cement reacts with water, and these phases play a crucial role in the setting and hardening of cement. When calcium aluminate is hydrated and combines with silicon, it becomes calcium silicate. The aluminium facilitates the reaction by acting as a catalyst. As a result, aluminium oxide is produced. The byproduct of a chemical process is hydrogen gas, which exits the cube through the bubbles formed during its setting.

$$CaO \cdot Al_2O_3 + H_2O \rightarrow Ca(OH)_2 + Al_2O_3 \quad \text{(Hydration)}$$
$$CaO \cdot Al_2O_3 \cdot xH_2O + Si \rightarrow xCaSiO_3 + 2Al + xH_2 \quad \text{(Expansion)}$$
$$CaO \cdot Al_2O_3 \cdot xH_2O + Si + H_2O + Al \rightarrow xCaSiO_3 + Al_2O_3 + xH_2 \quad \text{(Porosity)}$$

The M2 and M3 exhibit a surface area of 12.524 m^2/g and 11.514 m^2/g and the surface area of M1 is 6.910 m^2/g. This suggests that M2 and M3 are more porous than the conventional concrete M1. The result obtained from analyzing the correlation between the absorbed volume and the relative pressure as shown in Fig. 4a–c is categorized as a Hysteresis Loop of Type IV BET. The pores formed are macro-pores, and the typical pore size range of this category is between 2 and 50 nm. The adsorption volume for M2 varies between 5 and 35 cm^3/g, whereas it is between 2.5 and 22.5 cm^3/g for M3 and 3–16 cm^3/g for M1 cubes. The adsorption of all three elements commences at an approximate ratio of 0.5 (P/P_0).

Thermal conductivity of concrete cubes

Concrete M1 has a thermal conductivity of 0.295 W/mK and a thermal resistance of 3.47 K/W. Concrete M2 and M3 exhibit comparable outcomes, with thermal conductivities of 0.106 W/mK and 0.115 W/mK, respectively, and thermal resistances of 9.8 K/W and 9.3 K/W, making them the most efficient insulators. Concrete M4 has a thermal conductivity of 1.055 W/mK and a thermal resistance of 0.948 K/W.

Compressive strength of concrete cubes

A total of 36 concrete cubes were utilized for the water curing test, whereas another 36 cubes were employed for the acid curing test. Figure 5 displays the outcomes of the compression test (Fig. 5a) and mass measurement (Fig. 5b) of

Table 3 Comparison of conventional materials with replacement materials

Properties	Cement		Properties	Coarse aggregate	
	Conventional—OPC 53 cement	Replacement by functional PV layer waste		Conventional—gravel	Replacement by solar PV toughened glass waste
Pozzolanic properties	Demonstrates notable cementitious properties, interacting with water to generate C-S-H	Although its cementitious qualities are limited, it showed good pozzolanic behavior when finely crushed and used with solar panel adhesives	Strength contribution	Provides significant compressive strength and efficient load distribution	When used in concrete, it achieves 90% of the strength of normal concrete
Alkali-silica reactivity	May be vulnerable to ASR under certain conditions	Increased silica concentrations improved C-S-H bonding, resulting in the formation of cubic structures	Density/slump test	2.6 g/cm^3/89 mm	2.5 g/cm^3/95 mm
Compressive strength	Compressive strength of 53 MPa at 28 days. Initial strength of 30–35 MPa at 3 days	The fine particle size and large surface area of silica promoted cement reactivity during hydration, promoting early strength development and matrix density	Durability	Exceptionally resilient in many environments	Chemically stable and mechanically robust
Water demand	Moderate, necessitates a water–cement ratio of 0.35–0.50	Strength has been achieved with a comparable w/c ratio as traditional mixtures	Water adsorption	Influence of 0.5–2% depending upon the porosity of the aggregate	Impermeable, demonstrating no water absorption
Workability	Excellent workability	Exceptional workability, augmented by superplasticizers, improved the overall workability	Workability	Superb workability and less risk of segregation	Comparable workability to traditional concrete
Chemical compatibility	High levels of calcium silicates (C_3S, C_2S)	Silicon and adhesive enhanced the strength, while aluminium reacted to produce expansive concrete	Chemical compatibility	Superb compatibility with cement, guaranteeing strong adherence	Grinding the glass to eliminate additional functional layers generates the necessary adhesion with cement
Durability	Acceptable, although may be improved with enhancements	Analogous to that of traditional concrete	Alkali-silica reactivity	Absence of responses in the majority of the surroundings	No responses were seen throughout the experiment
Heat of hydration	Excessive heat generation may result in thermal cracking	Reduced heat production, beneficial for large-scale concrete applications	Thermal conductivity	0.28 W/mK	1.05 W/mK
Density/particle size/slump test	3.15 g/cm^3/<90 μ/89 mm	2.33 g/cm^3/<90 μ/80 mm	Impact and fracture resistance	Substantial resistance to compression and impact forces	Strength 10% lower than normal concrete
Sustainability	Increased CO_2 emissions (900 kg/ton)	Ecologically sustainable when sourced from repurposed solar panels	Sustainability	Quarrying has environmental impacts	Sustainable recyclable material that reduces landfill
Setting time	Preliminary setup about 30–45 min	Average duration was 44 min	Heat of hydration	Has little impact on heat output	Exerts little influence on the heat of hydration
Thermal properties	0.28 W/mK	0.10 W/mK	Chemical resistance	Effective, but may fail in hostile situations	Excellent chemical resistance, even under severe conditions (HCl acid)

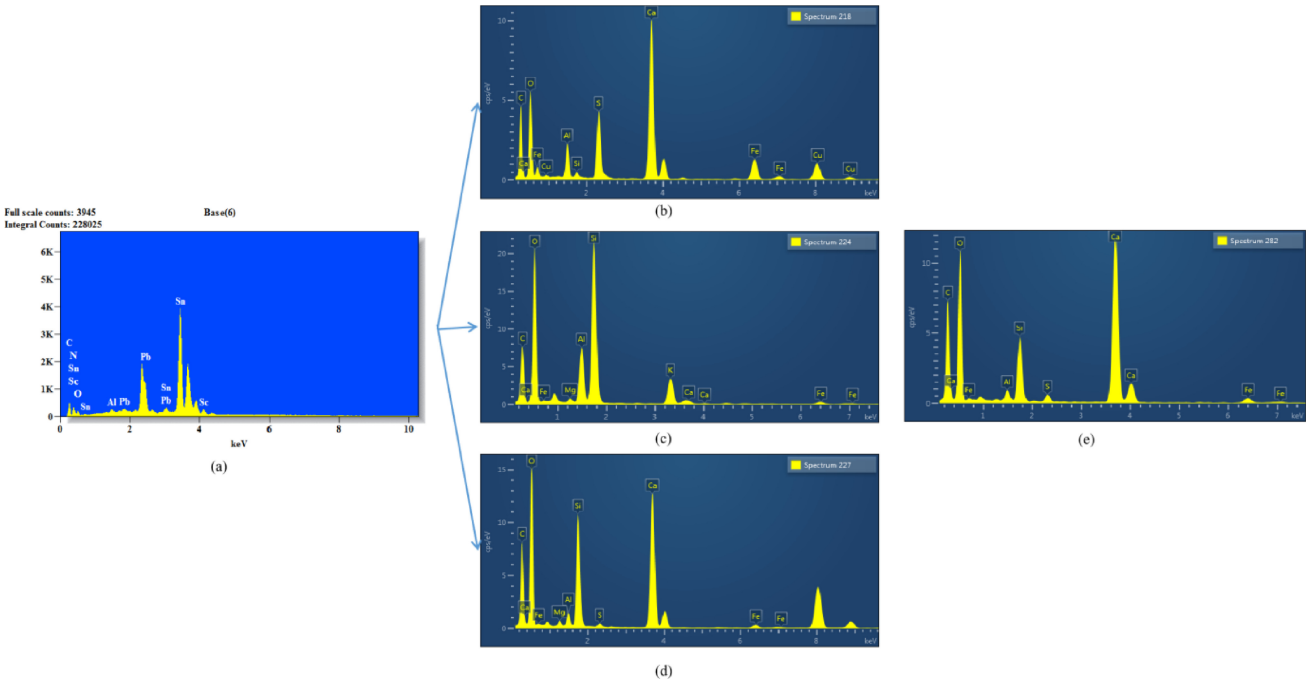


Fig. 3 **a** SEM of functional layer; **b** TEM of M2; **c** TEM of M3; **d** TEM of M4; **e** TEM of M1

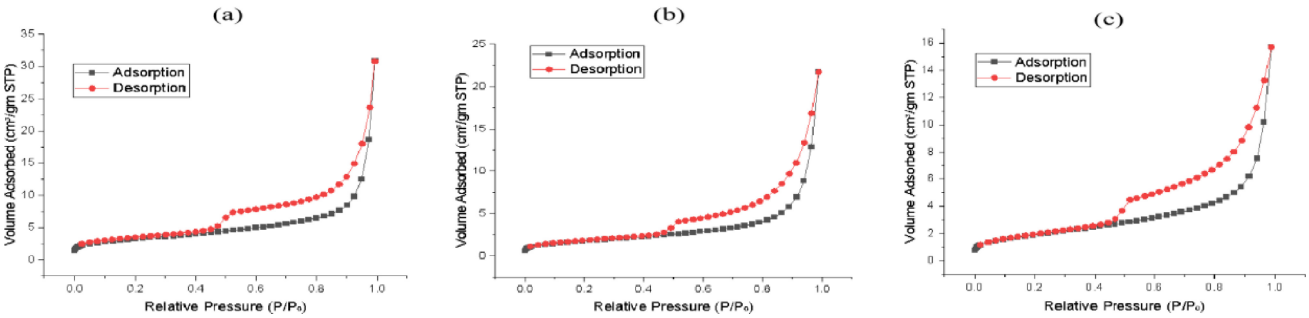


Fig. 4 BET analysis: **a** M2; **b** M3; **c** M1

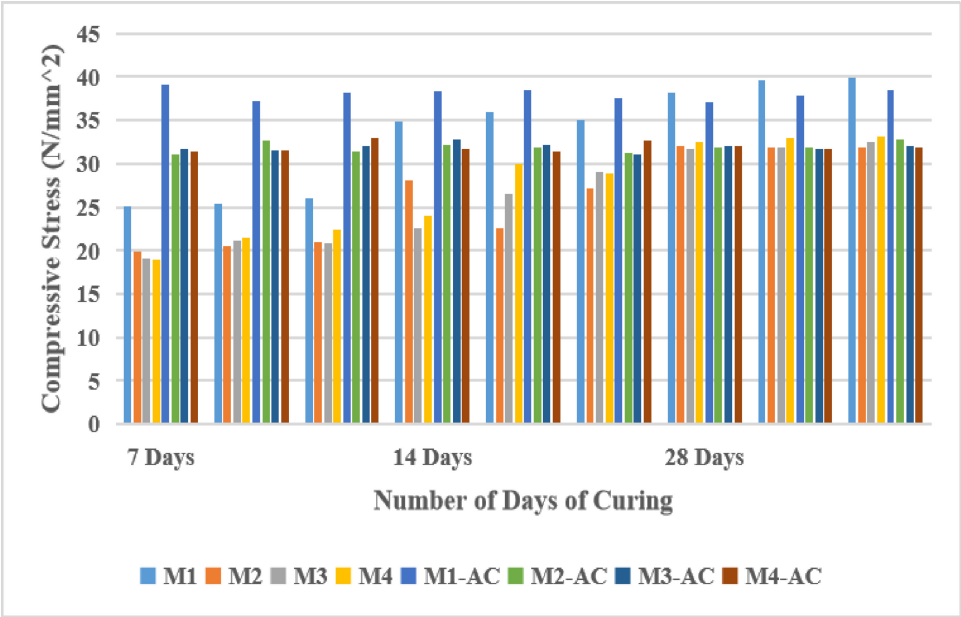
the cubes. The conventional concrete (M1) demonstrated strengths of 25.51 MPa at 7 days, 35.29 MPa at 14 days, and 39.2 MPa at 28 days, reflecting reliable early-age performance and continuous strength enhancement.

In comparison to the conventional cubes, the performance of the cubes with 10% cement and coarse aggregate replaced cubes (M2) exhibited a small reduction, beginning at 19.13 MPa after 7 days. Nevertheless, it rose to 25.94 MPa after 14 days and 31.78 MPa at 28 days, indicating that despite a decrease in strength, it has attained the designed range. The M3 concrete cubes also performed similarly to the M2 cubes in the compression test.

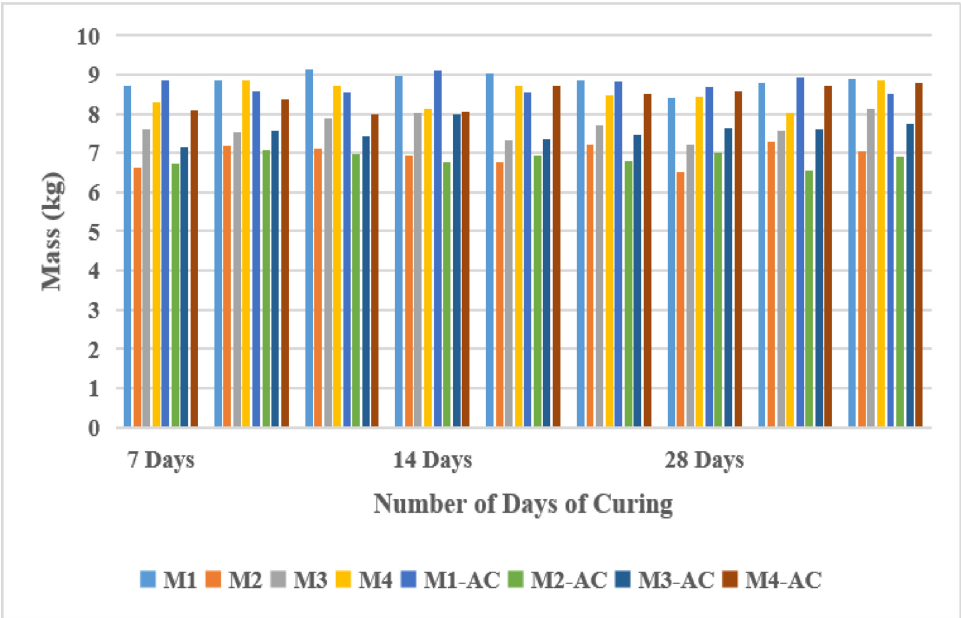
The utilization of PV toughened glass waste as a replacement for 10% of the coarse-aggregate (M4) resulted in compressive strengths of 20.30 MPa at 7 days, 27.58 MPa at 14 days, and 32.87 MPa at 28 days. The results demonstrate that the utilization of this alternative aggregate does not adversely impact concrete performance.

The acid-cured cubes with 10% cement and coarse aggregate replacement (M2-AC) demonstrated similar strength progression, ranging from 31.68 MPa at 7 days to 32 MPa at 28 days, signifying its suitability for practical applications. A further variant of the acid-cured cubes with 10% coarse aggregate substitution (M4-AC) had strength patterns akin to the standard cubes, attaining 31.94 MPa at 7 days, 31.93 MPa at 14 days, and 31.68 MPa at 28 days. None of the acid-cured cubes exhibited etching, damage, or discoloration on their surfaces.

The comprehensive strength range for all mixes was 31.75–39.17 MPa, suggesting that waste from solar photovoltaic systems can be effectively integrated into concrete while preserving adequate mechanical qualities. The results suggest that a feasible and sustainable method involves replacing up to 10% of both cement and coarse aggregate with waste derived from solar photovoltaic panels. This



(a)



(b)

Fig. 5 **a** Compressive stress analysis; **b** Mass of concrete cubes

approach aligns with sustainable construction practices while efficiently managing waste produced by solar panels.

Conclusion

An extensive examination is conducted to assess the performance of functional layers in place of cement and solar panel glass as a replacement for coarse aggregate. The following conclusions were derived from the study:

1. The concrete produced using recycled solar panels demonstrates the characteristics of lightweight concrete, with a density of 1860.91 kg/m^3 and 1943.79 kg/m^3.
2. This recycling technology can replace 11.69 billion tonnes of cement with functional layers, saving 46,760,000 TJ of energy and preventing 10.52 billion tonnes of CO_2 toxification.
3. Reduced cement production can save 16.37 billion tonnes of limestone, 1.75 billion tonnes of clay, 0.37

billion tonnes of silica sand, 0.05 billion tonnes of iron ore, and 0.23 billion tonnes of gypsum.

4. About 98.46 billion tonnes of solar PV panel toughened glass can replace conventional coarse aggregate in concrete up to 10%.
5. The concrete cubes derived from the recycled solar PV panels demonstrate porosity and expansion during the initial stage of the curing process. Thus, it can serve as a filler concrete.
6. SEM and TEM analyses demonstrate that recycling solar panels in concrete successfully encapsulates toxicity owing to the dominance of conventional materials in the mixture and the chemical processes happening during the curing process, therefore establishing this approach as a safe way of disposing of hazardous waste.
7. SEM and TEM analyses demonstrate adequate hydration and bonding of the components in the concrete samples.
8. The expansion concretes M2 and M3 have a surface area of 12.524 m^2/gm and 11.514 m^2/gm. The surface area of conventional concrete (M1) is 6.910 m^2/gm. The BET results of the three types of concretes are categorized as a Hysteresis Loop of Type IV BET.
9. The nitrogen adsorption capacity of M2 concrete ranges from 5 to 35 cm^3/g, whereas for M3, it ranges from 2.5 to 22.5 cm^3/g, and for M1, it ranges from 3 to 16 cm^3/g.
10. The thermal conductivity of the M2 and M3 concretes are 0.106 W/mK and 0.115 W/mK, which is notably lower than conventional concrete (M1) with a thermal conductivity of 0.295 W/mK.
11. The compressive strength of the novel concrete reaches the desired value for M25 grade concrete. The concrete cubes, which had cement replacement and coarse aggregate replacement, exhibited strengths ranging from 31.75 to 32.87 MPa when subjected to water and acid curing conditions.
12. The acid curing test findings confirmed that the proposed concrete did not cause any etching or damages to the cubes, demonstrating their ability to tolerate extreme corrosive environments and attain the desired strength in the compression test.

The outcomes of this study suggest that utilizing the used/waste solar PV panels as the substitute for conventional construction materials can effectively encapsulate the toxic elements in the concrete and reduce the production of virgin cement and coarse aggregate.

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Data availability Data generated at a central, large-scale facility, available upon request.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

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