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Sustainable Concrete Roof Tiles: Integrating Aluminium Foil, Fly Ash, Solar PV, and Management

Mukilan Poyyamozhi [1], Balasubramanian Murugesan [1,*], Rajamanickam Narayanamoorthi [2], Thenarasan Latha Abinaya [3], Mohammad Shorfuzzaman [4] and Yasser Aboelmagd [5,*]

[1] Department of Civil Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai 603203, India; mp6481@srmist.edu.in
[2] Department of Electrical and Electronics Engineering, SRM Institute of Science and Technology, Kattankulathur, Chennai 603203, India; narayanr@srmist.edu.in
[3] Faculty of Engineering & Technology, School of Architecture and Interior Design, Kattankulathur, Chennai 603203, India; abinayat@srmist.edu.in
[4] Department of Computer Science, College of Computers and Information Technology, Taif University, Taif 21944, Saudi Arabia; m.shorf@tu.edu.sa
[5] College of Engineering, University of Business and Technology, Jeddah 23435, Saudi Arabia
* Correspondence: balasubm1@srmist.edu.in (B.M.); yasser@ubt.edu.sa (Y.A.)

Abstract: This research investigates the use of municipal solid waste cremated fly ash as a viable substitute for natural sand in building methodologies, with a focus on sustainability. The waste material is used in the manufacturing of concrete roof tiles that are combined with solar PV systems, providing advantages in terms of both thermal comfort and improved energy efficiency. These tiles exhibit thermal insulation prowess by effectively preserving a 2-degree temperature differential and collecting heat from solar panels to enhance their energy-production efficiency. In order to enhance performance even further, aluminium foil is strategically placed on all four sides of the roof walls. The foil acts as a reflector, redirecting solar energy towards the tiles, which leads to a 5% boost in power generation. Particular alignments, such as positioning in an east-west or north-south direction, result in further enhancements in performance of 4% and 3%, respectively. This comprehensive approach not only confirms the use of waste materials for environmentally friendly construction but also emphasizes their crucial role in promoting energy-efficient building methods.

Keywords: solar PV; solid waste; aluminium foil; sustainability

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1. Introduction

The worldwide energy demand is escalating at an unparalleled pace, propelled by rapid industrialization, urbanization, and population expansion. The increase in energy consumption presents substantial obstacles to achieving sustainable development, since conventional energy sources like fossil fuels are responsible for environmental degradation, the release of greenhouse gases, and the exacerbation of climate change [1]. In light of the current global issues, it is imperative to swiftly shift towards sustainable approaches to power production that mitigate environmental harm and provide long-term energy stability. Solar power is distinguished among the numerous renewable energy sources due to its extensive capacity and comparatively little impact on the environment [2]. Utilizing photovoltaic (PV) systems and solar thermal technology is a viable approach to sustainably fulfill global energy demands by harnessing sun energy. Nevertheless, the implementation of solar technology also overlaps with the design and management of buildings, namely in relation to indoor comfort and energy efficiency [3].

The presence of solar radiation has a considerable impact on the indoor comfort of buildings, affecting both temperature and lighting conditions. Insufficient control of solar heat may result in excessive temperatures in buildings, more dependence on air conditioning systems, and elevated energy use [4]. On the other hand, the efficient use of solar energy may improve the level of comfort in terms of temperature, decrease the need for artificial lighting, and decrease energy expenses. Architectural design solutions, such as careful positioning, shading mechanisms, and the use of high-quality glass, are essential for maximizing solar energy absorption and minimizing its negative impact on inside spaces. By combining passive solar design concepts with active solar technology, it is possible to construct energy-efficient buildings that effectively use solar radiation and provide pleasant indoor conditions [5]. The dual task of satisfying increasing energy needs while guaranteeing comfortable building conditions emphasizes the significance of inventive and environmentally friendly methods in the construction sector.

The notion of sustainable construction is crucial in minimizing the environmental effects of buildings at every stage, including design, construction, operation, and destruction. Sustainable construction approaches include the use of renewable energy sources, energy-efficient building systems, and ecologically conscious materials [6]. An effective approach within this paradigm is integrating municipal solid waste (MSW) into building materials. Urbanization and population expansion are causing an increase in the amount of municipal solid waste (MSW). Landfilling, which is a prevalent technique of disposal, is causing land degradation, pollution, and resource depletion [7]. Using MSW in construction not only solves waste management problems but also promotes sustainable construction by preserving natural resources and minimizing the environmental footprint of building materials.

The use of cremated fly ash, a byproduct of municipal solid waste (MSW) incineration, as a substitute for fine aggregates in concrete has attracted significant interest. Fly ash has the capacity to augment the mechanical characteristics of concrete, such as its strength and durability, while simultaneously enhancing thermal comfort in buildings [8]. The use of fly ash in concrete enhances its thermal mass, enabling it to effectively modulate indoor temperatures by absorbing and gradually releasing heat. Consequently, this feature promotes the creation of indoor conditions that are both stable and pleasant [9]. The thermal mass effect reduces the need for heating and cooling, resulting in energy conservation and reduced emissions of greenhouse gases. The use of fly ash and other waste-derived materials in building is in accordance with the concepts of the circular economy, which regards waste as a valuable resource rather than a liability [10]. This method decreases the amount of garbage sent to landfills, preserves valuable natural resources like sand and gravel, and lessens the environmental impact of building operations. Moreover, it promotes the development of green construction standards and certifications that prioritize resource efficiency, waste reduction, and environmental responsibility. Through the use of sustainable practices, the construction sector may have a significant impact on reducing the effects of climate change and advancing environmental sustainability [11].

The incorporation of municipal solid waste (MSW) into building materials necessitates collaborative endeavors from several stakeholders, such as legislators, industry pioneers, academics, and communities. Governments may encourage the use of waste-derived resources by implementing regulations, providing subsidies, and establishing regulatory frameworks that support sustainable building methods [12]. In order to enhance the scientific understanding and practical implementation of these materials, it is essential for research institutions and industry experts to work together, guaranteeing that they adhere to rigorous performance and safety criteria. Public awareness and education are crucial as well, as well-informed communities may actively promote and embrace sustainable practices, hence increasing the market for environmentally friendly construction materials. Economic factors play a crucial role in encouraging the use of municipal solid waste (MSW) in buildings [13]. The cost-effectiveness of converting waste materials into building aggregates, as opposed to using standard extraction and production processes, may significantly influence the market's acceptance and use of this approach. Investments in waste processing infrastructure and technology may improve the efficiency and scalability of these activities, making them more economically feasible [14].

Public-private partnerships may expedite the creation of infrastructure by using resources and knowledge from both the public and private sectors to accomplish shared sustainability objectives. The worldwide energy demand can only be met sustainably by widely implementing renewable energy technology, with a special emphasis on solar power, alongside efforts to improve waste management and building sustainability [15]. Solar photovoltaic (PV) systems and solar thermal technologies have the potential to greatly diminish the dependence on fossil fuels, decrease the release of greenhouse gas emissions, and enhance energy security. Incorporating these technologies into architectural designs may further optimize energy efficiency and improve indoor comfort. For example, solar photovoltaic (PV) panels may be mounted on roofs or incorporated into the exteriors of buildings. They generate environmentally friendly power and also function as shade devices, reducing the amount of heat absorbed from the sun [16]. In addition, solar thermal systems may be used to fulfill diverse building energy requirements such as space heating, cooling, and water heating by harnessing the energy from the sun. By integrating renewable energy systems with energy-efficient building designs, it is possible to achieve net-zero energy structures that have an annual energy consumption equal to their energy production [17]. These buildings showcase the concepts of sustainable construction, illustrating the harmonious coexistence of renewable energy and creative design to attain both environmental and economic advantages.

The rising worldwide energy demand and the need for sustainable power production, together with the difficulty of ensuring indoor comfort in buildings, highlight the significance of inventive solutions in the construction sector [18]. Using cremated fly ash from municipal solid waste as a substitute for fine aggregates in building materials is a viable method for achieving sustainable construction. This method not only tackles waste-management difficulties but also improves the thermal comfort of buildings, leading to energy savings and promoting environmental sustainability [19]. Through the incorporation of renewable energy technology and the implementation of sustainable building methods, the construction industry has the potential to significantly contribute to the resolution of global energy concerns, mitigate greenhouse gas emissions, and advance the cause of a more sustainable future [20]. Coordinated endeavors including governments, business, academics, and communities are crucial for advancing these programs and fully realizing the promise of sustainable building and renewable energy. By implementing these initiatives, we can convert garbage into valuable assets, use solar energy, and construct a durable and environmentally friendly infrastructure that caters to the needs of both current and future generations [21].

Municipal solid waste (MSW) fly ash has distinctive chemical characteristics that significantly affect its efficacy in building materials. In contrast to coal fly ash, mostly made up of silica (SiO_2), alumina (Al_2O_3), and unburnt carbon, municipal solid waste (MSW) fly ash exhibits elevated levels of calcium (CaO), phosphates, chlorides, and heavy metals. The varied chemical composition significantly enhances the pozzolanic reactivity of MSW fly ash, resulting in improved hydration reactions when combined with cementitious materials. The elevated calcium oxide (CaO) concentration is essential since it interacts with silica to produce calcium silicate hydrates (C-S-H), the principal components accountable for strength enhancement in concrete. The presence of chlorides and phosphates impacts the setting time and may modify the hydration rate, leading to accelerated early strength development. Municipal solid waste fly ash includes trace amounts of metals, including zinc, lead, and copper, which, while requiring management for environmental safety, may also augment its reactivity under certain circumstances. The increased calcium concentration renders MSW fly ash more reactive than biomass or incinerator bottom ash (IBA), hence enhancing its efficacy in forming permanent cementitious linkages. Moreover, the inclusion of sulfur compounds in municipal solid waste fly ash enhances resistance to sulfate assaults, hence improving the long-term durability of materials subjected to harsh conditions. MSW fly ash has unique benefits compared to other waste materials such as coal fly ash, slag, and silica fume, especially in improving thermal comfort and strength. Regarding thermal properties, MSW fly ash has a thermal conductivity of 0.3 W/m.K and a specific heat capacity of 0.9 kJ/kg·K, which is superior for insulation relative to slag, which has a thermal conductivity of 1.5 W/m·K, and coal fly ash, which measures 0.4 W/m.K. Silica fume has a reduced heat conductivity of 0.5 W/m·K; however, it is more expensive. MSW fly ash has 40% silica and 20% alumina, resulting in a 25% enhancement in compressive strength. In contrast, coal fly ash contains 50% silica and yields a 20% enhancement in strength, whilst slag delivers a 15% boost attributable to its 40% CaO component. Silica fume, containing 90% silica, offers the greatest strength enhancement at 35%, although it is less cost-effective. In terms of durability, MSW fly ash decreases chloride ion permeability by 60%, which is equivalent to slag at 70% and coal fly ash at 50%. Silica fume provides optimal performance, decreasing permeability by 80%; nevertheless, its elevated cost restricts extensive use.

This study examines the use of cremated fly ash from municipal solid waste (MSW) as a replacement for sand in the manufacturing of concrete roof tiles. This research attempts to mitigate environmental problems related to waste disposal and decrease the use of natural sand resources by substituting fly ash for fine aggregate. Furthermore, this cutting-edge method incorporates solar photovoltaic (PV) systems directly into the concrete tiles, allowing them to serve as both construction materials and renewable energy producers. In order to improve both thermal comfort and energy efficiency, aluminium foil is used on the surface of the roof and side walls to effectively reflect solar radiation. The presence of this reflecting surface helps to reduce the amount of heat that is absorbed, therefore helping to maintain a pleasant home climate. This study demonstrates a sustainable approach to building design that promotes environmental stewardship and energy efficiency objectives by integrating waste reuse, renewable energy production, and improved thermal performance.

2. Literature Review

An empirical investigation was performed using aluminium reflectors to assess the influence of partial shade on solar panels. The research aimed to examine the impact of aluminium reflectors on solar panel efficiency while exposed to shadowing. Their study introduced a V-trough photovoltaic (PV) system that used readily available reflector materials in a low-temperature configuration [22]. This design aimed to enhance the system's performance without relying on expensive reflective materials. This implies that the selection of the reflector material may substantially influence the effectiveness of solar panels [23]. They investigated a photovoltaic-thermoelectric hybrid system using a GaAs solar cell and a front surface with nanostructures. The research discovered that by decreasing the amount of light reflected in specific ranges of wavelengths, it is possible to enhance the power generated by the system significantly. This suggests that improving the reflecting characteristics of solar panels might boost their total efficiency [24]. They conducted a study on small PV-CSP hybrid systems that use thermal energy storage to enhance their capacity to control the distribution of solar power. These findings indicate that the use of reflecting materials in solar systems may enhance their energy production and capacity factor. In addition, they conducted research on the use of compressed airflow for the purposes of cleaning and cooling solar photovoltaic panels. The study assessed the enhancements in energy production achieved by cleaning and cooling photovoltaic arrays in dry environments. This emphasizes the need for maintaining ideal working conditions for solar panels in order to optimize energy generation [25]. Researchers performed an empirical investigation on a novel hybrid PV/T bi-fluid system, including active cooling and self-cleaning methodologies. The findings demonstrated a direct correlation between electrical efficiency and PV module temperature, highlighting the need for temperature control in optimizing solar panel performance. Overall, the research indicates that including reflective materials, such as aluminium foil, might boost the solar reflectivity of panels and hence increase their power production. Researchers can enhance the energy output and overall effectiveness of photovoltaic systems by adjusting the reflective characteristics and using cooling and cleaning methods. Recent research has focused on the use of aluminium foil as a cooling method to enhance the performance of photovoltaic (PV) panels [26].

A model for a photovoltaic/thermal (PV/T) system was constructed that is both sun-tracked and cooled. The model incorporated an aluminium radiator to determine the temperature distribution over the surface of the PV panel [27]. Researchers performed an experiment where they used an aluminium heat sink as a cooling mechanism to lower the operational temperature of PV panels, leading to enhanced performance. They discovered that incorporating aluminium fins at the rear of photovoltaic (PV) panels resulted in improved power production and electrical efficiency. Researchers investigated several approaches to enhance the power generation of photovoltaic (PV) systems, in addition to cooling processes [28]. They conducted a comprehensive analysis of several maximum power point tracking (MPPT) strategies with the aim of enhancing the producing efficiency of photovoltaic (PV) systems [29]. They introduced an innovative droop-management technique aimed at optimizing the power generation of photovoltaic (PV) units in parallel inverter systems. They also integrated both active and passive cooling techniques in order to augment the electrical output of photovoltaic (PV) modules. Furthermore, experimental investigations were carried out to examine the influence of various cooling approaches on the performance of photovoltaic (PV) systems [30]. They examined how the energy performance of a hybrid PV/T bi-fluid system may be enhanced via the use of active cooling and self-cleaning methods. Researchers demonstrated a direct correlation between the electrical efficiency of the PV module and its temperature [31]. They investigated the use of a square cross-sectional two-phase closed thermosyphon to improve the cooling efficiency of photovoltaic (PV) panels. In general, the research indicated that including aluminium foil, heat sinks, fins, and other cooling techniques may significantly enhance the power output and efficiency of photovoltaic (PV) systems. In addition, the performance of solar PV arrays may be further improved by integrating active and passive cooling techniques, enhancing MPPT tactics, and applying innovative control approaches [32].

3. Material and Methods

3.1. Municipal Solid Waste Incinerated Fly Ash

On a daily basis, Chennai accumulates almost 5400 metric tons of rubbish, highlighting the significant waste-management issue faced by the city. In order to reduce the negative effects on the environment, the main emphasis is on improving the management of municipal solid waste (MSW). This includes strategies such as trash reduction, promoting recycling, and implementing sophisticated technology for converting waste into energy. As of now, incineration has replaced landfilling as the main way of disposing of Chennai's growing amount of municipal solid waste (MSW). Significantly, the city is home to two incinerator facilities located in Manali and Kodungaiyur, each capable of processing 200 metric tons of waste every day. These facilities generate fly ash from MSW incinerators, which has a high silica concentration. This makes it a viable alternative to traditional building materials such as sand [33].

Fly ash, obtained from the burning of municipal solid waste (MSW), undergoes thorough purification to remove contaminants prior to its use into concrete blends. Depending on the individual needs of the project, fly ash may be used to replace 20% to 40% of M-sand by weight. This substitution provides advantages such as improved durability of concrete and decreased materials expenses [34]. In addition, the use of fly ash helps to achieve environmental goals by reducing the negative impacts of trash incineration and enhancing the thermal comfort within buildings. Progressing further, developments in MSW processing technology and quality control procedures are essential for guaranteeing constant fly ash performance in building applications. Rigorous testing procedures are essential to confirm the quality and purity of fly ash, ensuring protection against pollutants that may undermine the integrity and performance of the material. Integrating materials obtained from municipal solid waste (MSW) into building projects is a sustainable approach to address waste-management difficulties in Chennai and other metropolitan areas [35]. This method helps satisfy infrastructure needs while also encouraging environmental stewardship and conserving resources. The physical properties and chemical properties of municipal solid waste incinerated fly ash is given in Tables 1 and 2.

Table 1. Physical properties of MSW.

Physical Properties	Value
Water absorption	14.08%
Specific gravity	2.4
Finess modulus	2.3
Loose bulk density	1105 kg/m^3
Compacted bulk density	1356 kg/m^3

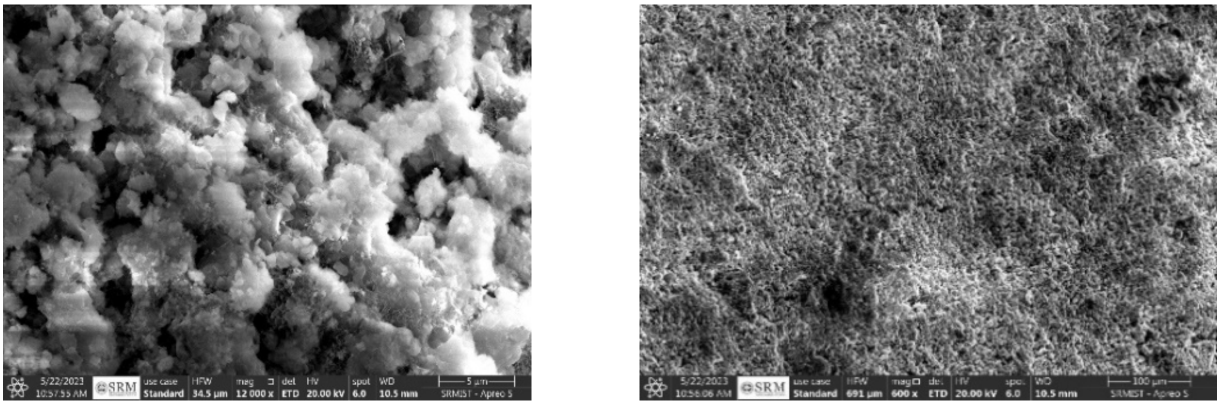
Table 2. Chemical properties of MSW.

Chemical Properties	Value%
SiO_2	64.75
Al_2O_3	0.78
Fe_2O_3	0.38
$CaCO_3$	14.85
Mg	0.74
C	15.53

3.2. Municipal Solid Waste Incinerated Fly Ash Micro Structure Analysis

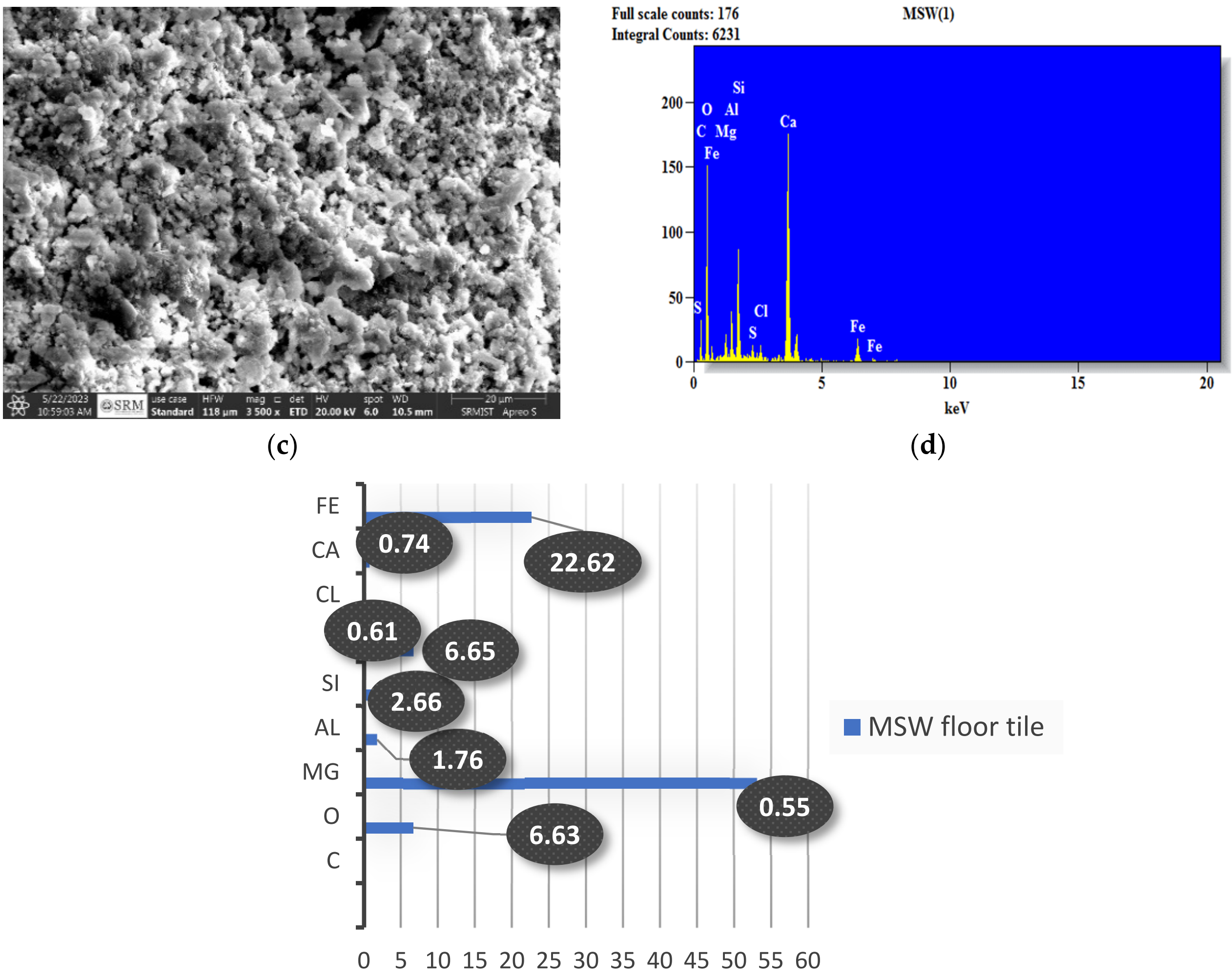
Figure 1 presents an extensive examination of municipal solid waste (MSW) burned fly ash tiles using diverse imaging methodologies. Figure 1a shows a scanning electron microscope (SEM) picture of the MSW floor tile at a magnification of 5 nm, highlighting the intricate surface architecture. Figure 1b displays an additional SEM picture at a magnification of 100 nm, illustrating the intermediate structural features. Figure 1c shows a SEM picture at 20 nm magnification, emphasizing the microstructural features of the tiles.

Figure 1d illustrates the energy-dispersive X-ray spectroscopy (EDS) picture used to ascertain the elemental composition of the MSW floor tiles. Figure 1e delineates the elemental composition, indicating iron (Fe) at 22.62%, calcium (Ca) at 0.74%, silicon (Si) at 2.66%, aluminum (Al) at 1.76%, oxygen (O) at 6.63%, and magnesium (Mg) at 0.55%. The inclusion of these materials, especially the elevated iron concentration, enhances the strength of the MSW floor tiles.



(**a**) (**b**)

Figure 1. *Cont.*



(**c**) (**d**)

(**e**)

Figure 1. (**a**) SEM image MSW floor tile 5 nm, (**b**) SEM image MSW floor tile 100 nm, (**c**) SEM image MSW floor tile 20 nm, (**d**) EDS image for MSW floor tiles, (**e**) MSW floor tile elements compositions.

3.3. Aluminium Foil Basic Test

In order to examine the solar-reflectivity characteristics of aluminium foil commonly found in households, two samples measuring 2 cm × 2 cm were obtained from a roll. One sample had the shiny side facing up, while the other had the dull side facing up. The samples underwent testing to quantify their surface roughness, reflectivity, and diffuse reflectivity. The roughness value is crucial as it directly impacts the foil's capacity to reflect solar radiation. Generally, a smoother surface, such as the bright side, has a lower roughness value, which in turn enhances its reflectivity. As shown in Figure 2, quantification of reflectivity and diffuse reflectivity values was conducted to assess the effectiveness of each side in reflecting direct sunlight and dispersing light, respectively. The bright side is anticipated to have a higher level of reflectivity, whereas the matte side may have more diffuse reflectance as a result of its rougher surface. In addition, Scanning electron microscopy (SEM) examination was performed to examine surface characteristics, detect any contaminants, and confirm the composition of the alloy. The microscopic examination guarantees a thorough understanding of the surface features, offering valuable insights into how these aspects impact the overall solar reflectivity performance of the aluminium foil. The outcomes of these studies are vital for enhancing the use of the material in solar energy applications, where effective light manipulation is of utmost importance.

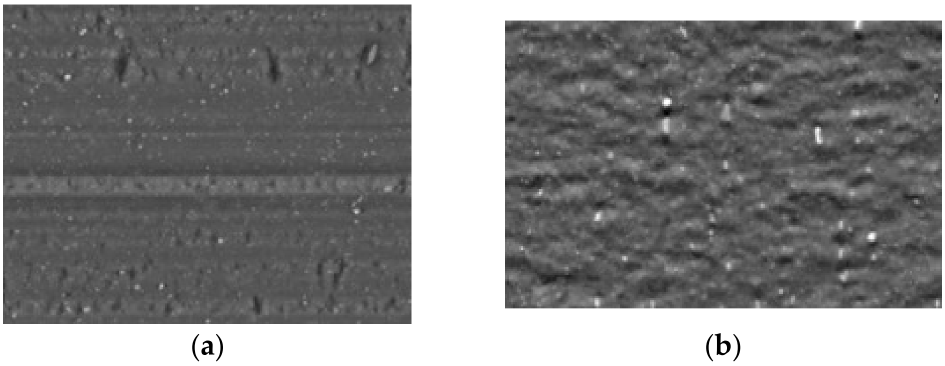

(**a**) (**b**)

Figure 2. (**a**) bright side (**b**) matte side.

3.3.1. Roughness

The STIL Microtopography CHR 150-N, offering a z accuracy of 10 nm, was employed for high-precision roughness assessment to enhance sample characterization [36]. Roughness maps for the bright and matte sides are detailed in Table 3, covering a 50 × 50 μm^2 area with a spatial resolution of 0.2 µm. Analysis revealed distinct surface features: the bright side exhibited parallel stripes, while the matte side displayed irregular uphill and downhill patterns. The bright side demonstrated significantly lower roughness (Ra = 0.210 ± 0.012 µm) compared to the matte side (Ra = 0.467 ± 0.079 µm). Prior to analysis, both sides were degreased with ethanol and stored in a controlled environment to prevent contamination and ensure data integrity. Based on the roughness test for aluminium foil, the values were given in Table 3.

Table 3. Roughness test for aluminium foil.

Test Name	Value
Roughness Value	
Bright Side	(Ra = 0.210 ± 0.012 µm)
Matte Side	(Ra = 0.467 ± 0.079 µm).

3.3.2. SEM Analysis for Aluminium Foil

Scanning electron microscopy (SEM) examination was performed on two samples measuring 2 cm × 2 cm, obtained from a standard aluminium foil roll often seen in supermarkets. The thickness of the foil was determined to be 12.5 ± 2.5 µm. Figure 2 displays scanning electron microscope (SEM) pictures of the foil surfaces, showcasing notable characteristics. It was discovered that there were parallel and uniformly distributed stripes, which were most likely caused by twin roll mill markings during the production process. In contrast, the matte side exhibited a less uniform texture without distinct stripes but contained noticeable accumulations of aluminium fines, which are characterized as little white particles. The EDS analysis revealed that the alloy composition was mostly composed of aluminium (93.84%), with smaller amounts of oxygen (4.14%), calcium (1.20%), and iron (0.82%). These results indicate that the foil is probably made of an aluminium alloy that has been specifically designed to have high strength, the capacity to be easily shaped, and rigidity. These properties are crucial for its use in packaging and other sectors. The scanning electron microscopy (SEM) examination yielded crucial information about the surface structure, presence of debris, and composition of the alloy. This investigation greatly contributed to a thorough comprehension of the foil's structural properties and performance features. (a) The bright side and (b) the matte side are shown in Figure 2.

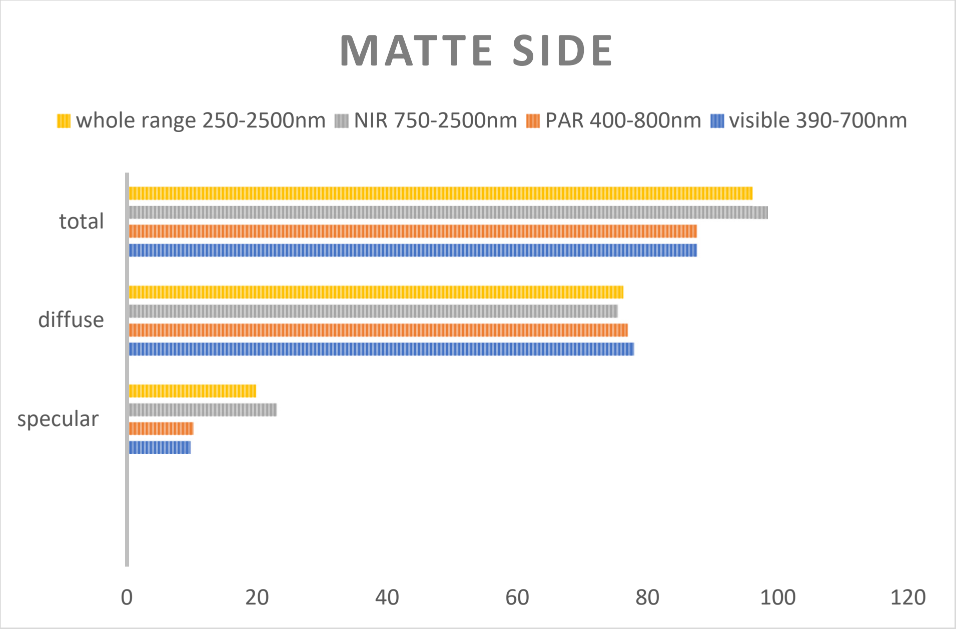
3.3.3. Reflectivity Measurements

The reflectivity measurements were performed using a quartz tungsten-halogen lamp to generate visible-IR light and a deuterium arc lamp to generate ultraviolet light [37].

The measurements used a PMT detector for UV-vis light and a cooled PbS detector for near-infrared light. All of these components were combined into the Cary 5000 spectrophotometer, manufactured by Agilent, Texas, USA. The device operates within a spectral range of 250 to 2500 nm and is located within a DRA2500 integrating sphere with a diameter of 115 mm and a Spectralon SRS-99 coating. This configuration guarantees precise measurement of the scattering of light from a surface, where a regular incoming beam of light shines on the sample via a round opening. Contrary to the specular reflection component, which travels straight through the aperture, the diffuse component experiences several reflections before reaching the detectors. The aperture size used was 9.12 mm × 5.10 mm^2, which corresponds to ±2.4 azimuth and 1.3 elevation. This aperture size achieved a solid angle of approximately 0.005 sr, making it suitable for accurately measuring diffuse reflectivity angles. These angles are typically within the range of 0.01 sr for specular or near-specular reflections.

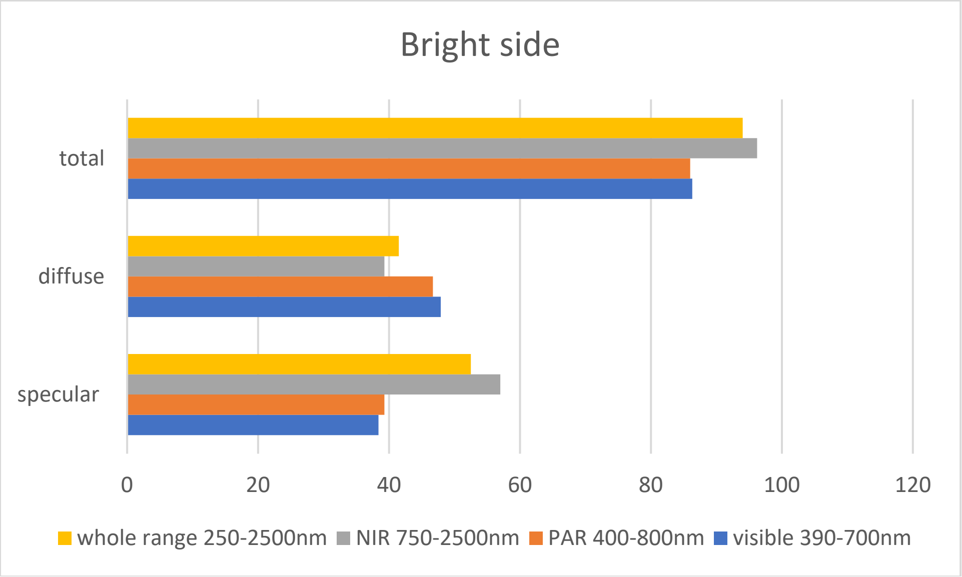
3.3.4. Reflectivity over Different Spectral Range

Figure 3 presents approximate integral reflectivity values for convenience, without taking into account the spectrum of the light source. It is important to be cautious when utilizing total reflectivity numbers, yet the flat profiles may be useful in some situations [38]. The angular distribution of reflected photons is a crucial factor in the literature on aluminium reflectivity. Although not investigated in this particular study, previous research suggests that the range of diffuse scattering from anodized aluminium is usually within ±5 degrees and conforms to a Gaussian distribution. Stripes created by twin roll mills have a tendency to affect the orientation of reflected light. The scattered reflected radiation constantly conforms to a normal distribution, regardless of whether the incoming light is perpendicular or parallel to these stripes. A parallel alignment (±8 degrees) leads to a more pronounced scattering effect compared to a perpendicular alignment (±16 degrees). Furthermore, research has examined the impact of the angle at which light strikes a surface on its ability to reflect light, finding substantial variations in the total amount of reflected light between 0 and 78 degrees. However, the diffuse component of reflection experiences only a little rise. Reflectivity over different spectral ranges are shown in Figure 3.



(a)

Figure 3. *Cont.*



(**b**)

Figure 3. Reflectivity over different spectral range: (**a**) matte side and (**b**) bright side.

3.3.5. Aluminium Foil SRI Value

The solar reflectance of aluminium foil, which usually falls between 0.85 and 0.95 (equivalent to 85% to 95%), dictates its capacity to reflect solar radiation. This, in turn, reduces heat transmission by deflecting a substantial percentage of the sun's rays. This characteristic is essential for maintaining acceptable indoor temperatures by reducing heat absorption from direct solar exposure. In addition, aluminium foil has a low sunlight-absorption rate, usually below 0.10 (or 10%), which enhances its ability to keep interior environments from becoming too hot. Aluminium foil has a low thermal emissivity, usually ranging from 0.03 to 0.05. This makes it very effective in reflecting solar radiation straight onto solar photovoltaic (PV) panels. As a result, it improves sustainable energy practices and boosts power production. In addition to generating power, this technology improves the comfort of the interior, making it a sustainable and environmentally beneficial option for construction practices and energy management tactics [39]. The use of aluminium foil in sustainable building is crucial due to its low thermal emissivity, high solar reflectance, and moderate solar absorption. These properties contribute to enhancing energy efficiency and interior comfort.

4. Municipal Solid Waste Incinerated Fly Ash Concrete Roof Tiles

The production method of M25-grade concrete for making concrete roof tiles emphasizes precise processes to provide strong structural integrity, long-term durability, and strict compliance with environmental norms. A crucial aspect of this procedure is replacing 30% of the overall sand content with fly ash, which is obtained from the burning of municipal solid trash. This replacement not only improves the efficiency of materials, but also makes a substantial contribution to environmental conservation by decreasing reliance on natural sand resources [40]. The manufacturing process of these tiles begins with a 6 mm aggregate top layer, which is then followed by further layers that are compressed using a vibrating table to achieve ideal consolidation. The first layer consists of smaller aggregates, while the following layers include aggregates that are between 6 mm and 12 mm in size. This ensures that the tile construction has consistent strength and resistance. To provide sufficient hydration and strong strength development throughout the curing process, a specific water–cement ratio of 0.40 is carefully maintained. The eco-friendly concrete tiles, with dimensions of 30 × 30 × 1.5 cm, are particularly designed for a range of roofing uses, providing both adaptability and sustainability. Their design incorporates elements such as built-in solar panel fittings, which make it easy to install solar panels with integrated mounting projections and flexible wiring connections. This revolutionary design not only improves the performance of the tiles but also facilitates the incorporation of renewable energy, in line with contemporary architectural and environmental trends that promote sustainable construction practices [41]. The Mix Ratio is given in Table 4.

Table 4. Mix Ratio.

Sample	Cement	M-Sand	Torched Fly Ash	Course Aggregate (6 mm)	Course Aggregate (12 mm)	W/C Ratio
Torched Fly Ash Roof Tiles layer one	1	0.7	0.3	-	2	0.4
Torched Fly Ash Roof Tiles layer two	1	1.4	0.6	1	3	0.4

4.1. Municipal Solid Waste Incinerated Fly Concrete Roof Tiles Temperature Analysis

The inclusion of a K-type thermocouple sensor in the integrated data recorder provides a sophisticated approach to monitor temperature variations in torched fly ash roof tiles. This configuration enables the simultaneous monitoring of temperatures on both the top and lower surfaces, allowing a full assessment of temperature fluctuations [41]. K-type thermocouples are chosen for their robustness and dependability in high-temperature settings, guaranteeing accurate measurement precision throughout the monitoring procedure. The data logger consistently captures and stores temperature data for a duration of 30 days, offering significant insights into the thermal dynamics and performance trends of the roof tiles.

The measured mean temperature difference of 2 degrees Celsius between the top and lower layers is crucial for evaluating the insulation efficacy, heat endurance, and overall energy efficiency of the tiles. The use of data in this technique enables designers and materials engineers to make well-informed judgments on the optimization of performance and selection of materials for roof tile applications. The graphical depiction of the 30-day average temperature data provides a clear visualization and explanation of patterns, enabling proactive modifications and enhancements in design and production procedures. In conclusion, using extensive temperature data improves the sustainability and operational efficiency of roof tile installations, guaranteeing that they satisfy strict performance criteria throughout their lifespan. Solar panel integration in torched fly ash roof tiles temperature analysis is shown in Figure 4, and solar panel integration in torched fly ash roof tiles temperature and difference is shown in Figure 5.

Figure 4. Solar panel integration in torched fly ash roof tiles temperature analysis.

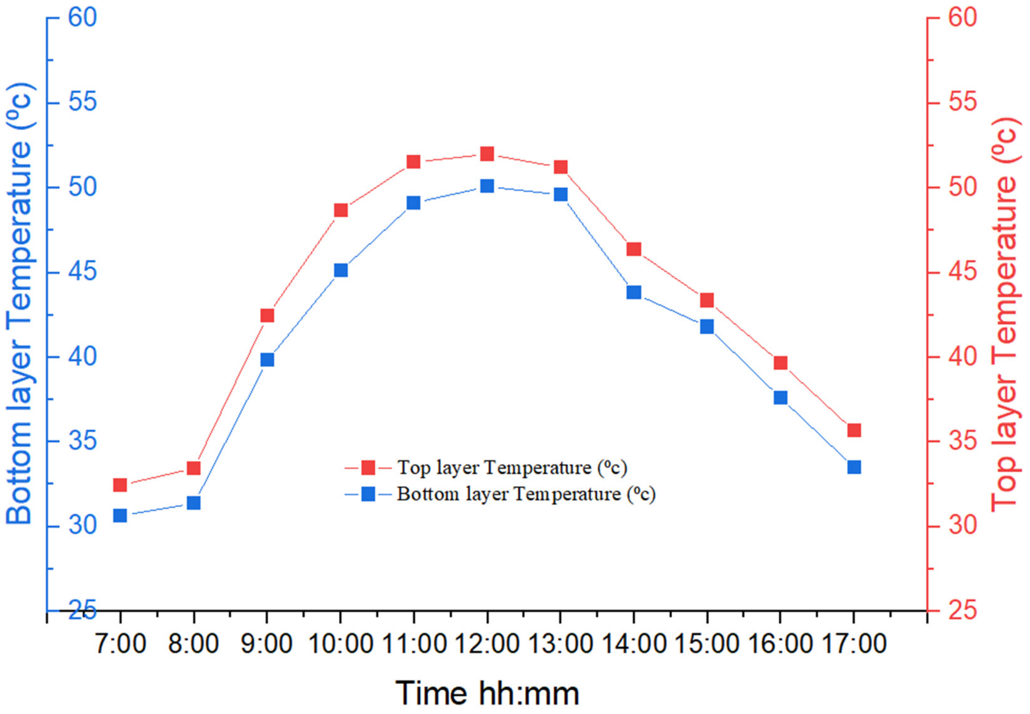


Figure 5. Solar panel integration in torched fly ash roof tiles temperature and difference.

4.2. Solar Reflectance

Concrete roof tiles with a solar reflectance value of 0.8 play a crucial role in enhancing thermal management and interior comfort. Due to their high solar reflectance, they effectively prevent the sun's rays from entering and maintain a low temperature within the structure. These tiles effectively reduce indoor temperatures, particularly during hot weather, by reflecting a significant portion of the sun's energy [42]. Occupants' enhanced comfort and reduced reliance on mechanical cooling systems result in energy savings and environmental benefits. Concrete roof tiles with high solar reflection are an attractive choice for sustainable building practices because they improve energy efficiency and occupant well-being. This is due to their inherent thermal comfort characteristic.

4.3. Solar Absorption

The solar absorption index of concrete roof tiles, which measures their ability to absorb solar energy, is very low at 0.259. This characteristic is essential for enhancing the suitability of these roof tiles for thermal comfort. These tiles help maintain lower interior temperatures by absorbing less solar radiation, therefore minimizing heat transfer into the building structure. Possessing this characteristic is particularly advantageous in regions with abundant sunlight or during periods of intense sunshine. By using these concrete roof tiles, buildings may experience less heat gain, resulting in increased occupant comfort and decreased reliance on mechanical cooling systems. Hence, by promoting energy efficiency and enhancing the indoor ambiance, these tiles significantly contribute to sustainable building methods.

4.4. Thermal Emissivity

The thermal emissivity of tiles is a crucial consideration in selecting building materials, particularly when it reaches a value of 0.81. This characteristic demonstrates the effectiveness of the tiles in dissipating heat. Tiles with a high thermal emissivity are very suitable for various construction projects. Their main purpose is to enhance interior comfort while reducing the burden on mechanical cooling systems, hence promoting energy efficiency. The advantages of this are amplified in hot regions or in buildings with much glass. High thermal emissivity tiles may enhance the longevity of roofing materials by reducing thermal stress, resulting in less maintenance requirements and increased durability. High thermal emissivity tiles provide the added advantages of enhanced energy efficiency and decreased emissions of greenhouse gases in green building projects. The solar relativity index for tiles is shown in Table 5.

Table 5. Solar relativity index for tiles.

Tiles SRI Value	Value
Solar reflectivity	0.8
Solar absorption	0.259
Thermal emissivity	0.81

5. The Influence of Building Orientation on Solar Photovoltaic Power Generation

The alignment and positioning of solar photovoltaic (PV) panels are crucial elements in optimising solar energy absorption and total electricity production. The direction of a building is essential in affecting the effectiveness and productivity of solar PV systems [43]. This scientific discussion explores many elements of maximising solar PV power production by strategically aligning buildings. It covers optimum alignment based on geographical location, tilt angle considerations, shading study, and roof design options to maximise power generation.

5.1. Ideal Alignment

The geographical position of the structure mainly dictates the most favourable alignment of photovoltaic (PV) panels. For optimal performance, photovoltaic panels in the Northern Hemisphere should be oriented towards the actual south direction. This orientation guarantees optimal sunshine exposure year-round since the sun is mainly positioned to the south during mid-day in these areas [44]. Orienting the panels towards the south allows optimal solar radiation collection, particularly during peak sunshine hours, resulting in maximum energy output. In contrast, in the southern hemisphere, it is optimal for PV panels to be oriented towards the true north. This is because the sun is mainly positioned to the north during mid-day in these areas. North-facing solar panels in the southern hemisphere will get the most solar energy possible throughout the year, maximising electricity output. Buildings near the equator may need a different ideal orientation owing to the even dispersion of sunshine throughout the day. An east or west orientation would maximise sunshine exposure in the mornings and afternoons. East-oriented panels will create more electrical output during the morning when the sun ascends, but west-oriented panels will produce higher power during the afternoon and nighttime.

5.2. Angle of Inclination

The inclination angle of solar photovoltaic (PV) panels is a vital determinant in optimising sun irradiation and electricity production. The ideal inclination angle is usually around the latitude of the specific site [45]. For example, at a latitude of 40° N, it is optimal to tilt the panels at a 40° angle to collect the most significant quantity of sunlight. This angle ensures that the panels are positioned at a right angle to the sun’s beams at the equinoxes, maximising the capture of solar energy. When installing fixed solar panels, it is recommended to adjust the tilt angle to be near the latitude to optimise energy collection throughout the year. Nevertheless, the efficiency of solar PV systems may be further improved by using adjustable or tracking systems. These systems can modify the tilt angle in response to seasonal variations, allowing for more accurate sun trajectory tracking. When the sun is positioned higher in the sky during the summer, a less steep tilt angle may be more efficient. Conversely, in winter, a steeper tilt angle can be advantageous for capturing sunlight at lower angles.

5.3. Factors to Consider Regarding Shading

Shading substantially impacts the effectiveness of solar photovoltaic (PV) systems. Even a slight shading on one panel may significantly affect the overall performance of the whole array, depending on how the panels are set up and what kind they are. Hence, it is essential to guarantee that adjacent structures, foliage, or other barriers do not obstruct photovoltaic (PV) panels. An exhaustive shading study must be conducted to ascertain the optimal positioning of PV panels on the building [46]. This research entails evaluating the location for possible obstructions that may cast shadows and considering the sun's trajectory throughout the year. Tools such as solar pathfinders or software-based modelling may mimic shading patterns and improve the positioning of solar panels. It is crucial to minimise shadowing between 9 AM and 3 PM, the peak solar hours, to maximise electricity output.

5.4. Orientation and Design of the Roof

The efficiency of solar PV systems may also be affected by the design and orientation of the roof. When dealing with structures with sloping roofs, it is essential to consider the current orientation and tilt angle [47]. If the orientation is favourable, panels may often be directly fixed on the roof. Flat roofs may accommodate PV panels by mounting them on racks to obtain the required tilt and orientation. Maximising sun exposure and electricity production may be achieved using all four sides of the roof. Installing photovoltaic (PV) panels on many sides can guarantee that various arrays collect sunlight at different times of the day. This helps to even out power production and potentially increases the overall electricity output. Aluminium foil and other reflective materials may be used on the roof to increase reflectivity, reducing the passage of heat to the building and enhancing thermal comfort. Reflective surfaces enhance the redirection of sunlight onto the PV panels, augmenting the total solar energy received. This strategy is very beneficial for optimising electricity generation in regions with limited rooftop area. In addition, using reflecting surfaces may effectively limit heat transmission to the building, enhancing thermal comfort and decreasing the need for cooling, resulting in lower cooling loads.

5.5. Influence of Orientation on Power Generation

The positioning of photovoltaic panels has a direct influence on their electricity production throughout the course of the day [47]. Below are the overarching patterns for electricity production dependent on orientation: East-oriented solar panels produce higher electricity output during the morning hours. East-facing panels may typically catch about 85–90% of the entire energy that south-facing panels would gather during the day. West-oriented solar panels produce higher energy output throughout the afternoon. West-facing panels can catch around 85–90% of the energy that south-facing panels can capture, the same as east-facing panels. South-facing solar panels in the Northern Hemisphere generate electricity evenly throughout the day, resulting in the highest total daily production. Typically, south-facing panels are regarded as the norm for achieving optimum efficiency since they may capture almost 100% of the ideal energy. North-facing panels (Southern Hemisphere): Like south-facing panels in the Northern Hemisphere, these panels generate electricity evenly throughout the day. North-facing solar panels in the Southern Hemisphere can collect almost all of the maximum energy available.

5.6. Illustrative Situation

Construction in 40° N Latitude: To demonstrate the influence of building orientation on solar photovoltaic (PV) power production, let's examine a building situated at a latitude of 40° N: Optimal Orientation. The photovoltaic panels must be oriented towards true south to maximize sunlight capture throughout the year. Optimal Tilt Angle: It is recommended to tilt the panels at a 40° angle, in line with the latitude, to optimise sun exposure. Perform a shade study to verify that no substantial shading occurs between 9 AM and 3 PM, which are the hours with the highest amount of sunshine, to maximise electricity production. To optimise solar energy collection, the building may strategically position the PV panels to face true south and modify the tilt angle to 40°. Maximising the system's efficiency by minimising shade during the peak hours increases power production.

6. Municipal Solid Waste Incinerated Fly Ash Tiles Integrated with Solar PV

The integration of municipal solid waste burned fly ash roof tiles with a solar PV system is a novel method to improve the sustainability and energy efficiency of buildings. These tiles have a secondary function as thermal comfort tiles, efficiently controlling building temperatures via their distinctive composition. These tiles reduce the amount of heat on the structure by absorbing and dispersing heat from the sun, especially from the bottom of the solar panels mounted on them. The temperature regulation not only enhances the comfort of the inhabitants but also greatly enhances the efficiency of the integrated solar PV system [40].

Strategically positioning aluminium foil on the walls of the roof is vital for improving the efficiency of integrated roof tiles made from cremated fly ash and equipped with solar PV systems. The aluminium foil reflects solar radiation away from the building's side walls, therefore preventing excessive heat absorption into the structure. The redirected solar radiation then interacts with the roof tiles, which are specifically engineered to effectively collect and harness solar energy. The synergistic impact of decreasing direct solar heat uptake on the structure and channeling reflected radiation towards the solar PV tiles amplifies the total efficiency of the system. This integration improves the thermal comfort of the structure and the energy output of the solar PV system, making it a feasible and eco-friendly option for energy-efficient structures.

6.1. Prototype

A wooden box of 60 cm × 75 cm × 15 cm is used to assess the effectiveness of roof tiles made from cremated fly ash obtained from municipal solid waste, in conjunction with solar photovoltaic (PV) systems. The box is constructed with duplicated roof side walls that are covered in aluminium foil to amplify the reflection of solar radiation onto the tiles, leading to enhanced energy absorption. In this regulated environment, the tiles are securely attached and connected to a solar panel that is accompanied by a data logger. The study used 5-watt, 12-volt polycrystalline solar panels. Four panels are used, consisting of two panels without integrated tiles and two panels with integrated tiles. During a span of 15 days, the data logger records power output measurements every hour from all four primary directions: north, south, east, and west. The data is methodically collected and analysed to provide an average power output profile for each direction. The graphical representation in Figure 6 offers a comprehensive overview of the tiles' performance under diverse solar conditions, facilitating a detailed assessment of their efficiency and suitability for sustainable construction. This rigorous testing method guarantees accurate assessment and improvement of energy-producing capabilities in real-world scenarios.

Figure 6. As shown here, all sides are covered with aluminium foil.

6.2. Normal Side Wall without Aluminium Foil

Figure 7 illustrates that the solar PV tiles, when not equipped with aluminium foil on the roof side walls, achieve a mere 1% efficiency in power generation. The tiles' poor effectiveness is due to their direct exposure to solar radiation without the presence of reflecting surfaces to divert and boost sunlight absorption. The lack of aluminium foil leads to a substantial part of the incoming solar energy being inefficiently used by the tiles, resulting in low power production. This image highlights the crucial importance of using reflecting materials to enhance the performance of integrated solar PV systems. It emphasizes the need for considering design factors comprehensively in order to achieve maximum energy collection and conversion efficiency. Normal side wall with normal solar PV and torched fly ash integrated solar PV, and normal side wall power out for normal PV and torched fly ash integrated solar PV, are shown in Figures 7 and 8.

Figure 7. Normal side wall with normal solar PV and torched fly ash integrated solar PV.

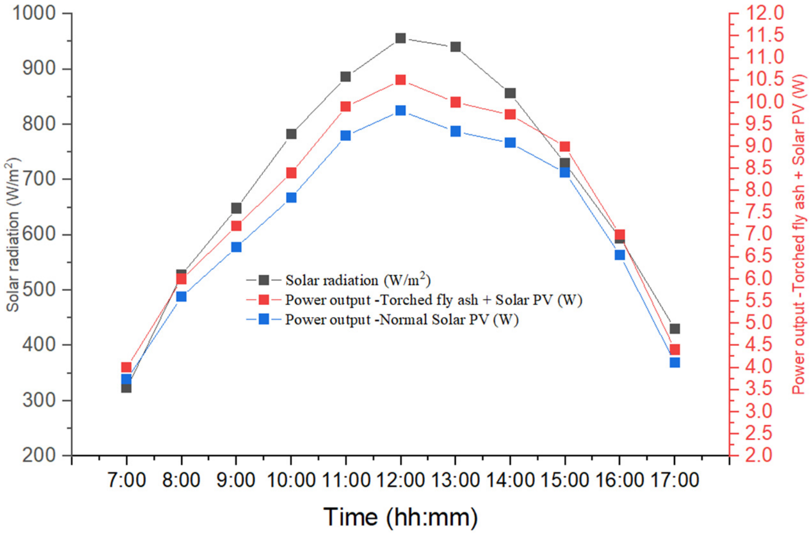


Figure 8. Normal side wall power out for normal PV and torched fly ash integrated solar PV.

6.3. Normal Side Wall vs. North-South-Side-Placed Aluminium Foil

Figure 8 demonstrates that the power output of the integrated municipal solid waste burned fly ash roof tiles with solar PV systems increases by 3% when aluminium foil is placed on the north and south sides of the roof. The increase in solar radiation onto the roof tiles is directly related to the reflecting qualities of the foil, which redirect the solar energy. The graph illustrates how the use of aluminium foil enhances the absorption of sunlight, resulting in increased efficiency in generating energy from the solar PV system. This improvement highlights the tangible advantages of using reflecting materials to optimize energy absorption and improve the overall effectiveness of eco-friendly building technology. The aluminium foil in the north-south direction, and the power out difference with and without aluminium foil in the north-south direction, are shown in Figures 9 and 10.

Figure 9. This image shows the aluminium foil in the north-south direction.

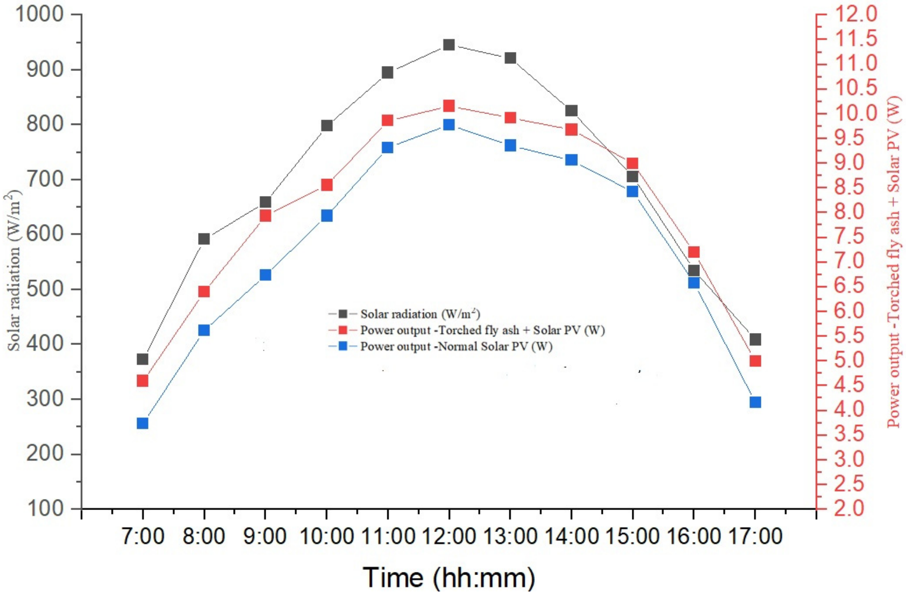


Figure 10. Power out difference with and without aluminium foil in the north-south direction.

6.4. Normal Side Wall vs. East to West-Placed Aluminium Foil

Figure 11 illustrates that the installation of aluminium foil on the eastern and western sides of the building's roof walls leads to a significant 4% enhancement in the power output of the integrated municipal solid waste incinerated fly ash roof tiles with solar PV systems, as compared to the power output without foil on these sides. The reason for this rise is the aluminium foil's capacity to reflect and redirect solar energy onto the roof tiles throughout the day as the sun travels from east to west. The graph demonstrates how the strategic positioning maximizes the absorption of solar radiation, thereby improving the efficiency of power production from the solar PV system. This method emphasizes the substantial influence of reflecting materials in optimizing energy absorption and enhancing the overall efficiency of sustainable building systems. Aluminium foil in the east-west direction, and the power out difference with and without aluminium foil in the east-west direction, are shown in Figures 11 and 12.

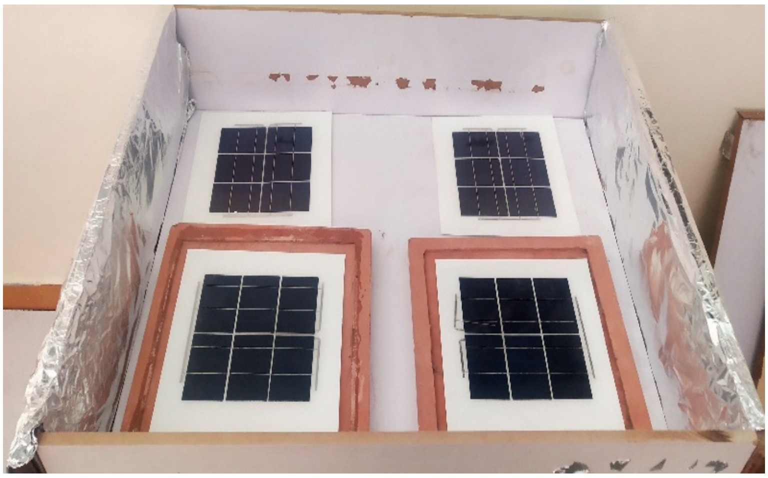


Figure 11. This image shows the aluminium foil in the east-west direction.

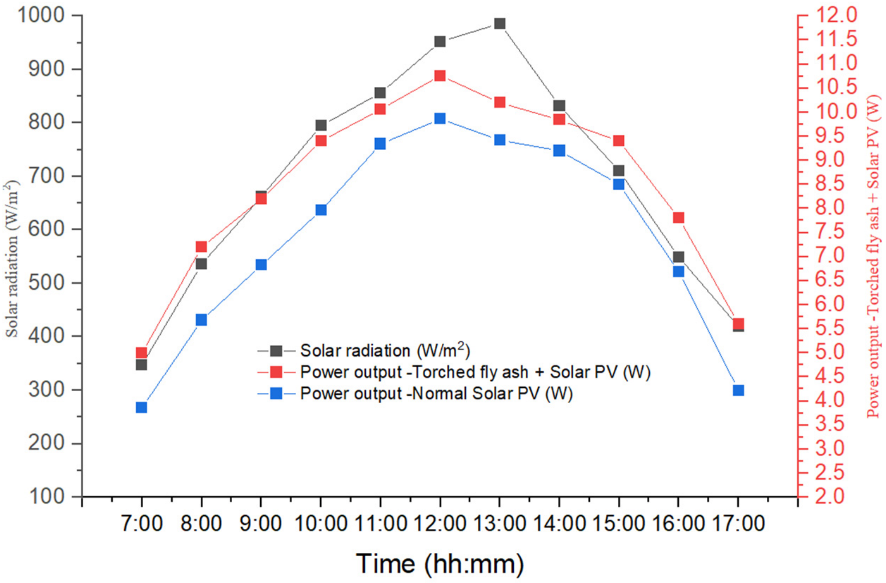


Figure 12. Power out difference with and without aluminium foil in the east-west direction.

6.5. Normal Side Wall vs. All the Four Sides Are Covered with Aluminium Foil

Figure 13 illustrates that completely enveloping the roof walls of the building with aluminium foil on all four sides (north, south, east, and west) leads to a significant 5% enhancement in the power generation of the integrated municipal solid waste burned fly ash roof tiles equipped with solar photovoltaic (PV) systems. This method efficiently harnesses the reflecting characteristics of aluminium foil to redirect and intensify solar energy onto the roof tiles throughout the whole day. The graph illustrates how fully covering the roof walls enhances the absorption of solar radiation, leading to a substantial increase in the efficiency of power production from the solar PV system. In addition, the foil's coverage of all sides serves to reduce the absorption of waste heat by the side walls, therefore enhancing the system's power production and overall energy efficiency. This comprehensive solution highlights the significance of using reflecting materials to optimize the consumption of renewable energy and improve the efficiency of sustainable building technology. Aluminium foil covering all four directions, and power out for all sides covered with aluminium foil, are shown in Figures 13 and 14.

Figure 13. This image shows aluminium foil covering all four directions.

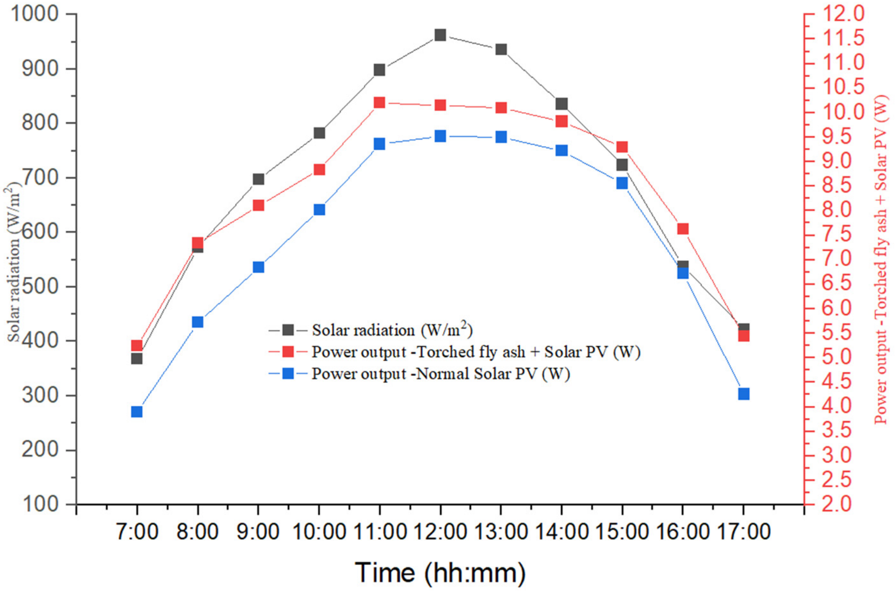


Figure 14. Power out for all sides covered with aluminium foil.

7. Conclusions

Utilizing cremated fly ash from municipal solid waste (MSW) as a substitute for natural sand, including manufactured sand, in concrete roof tiles presents considerable progress in sustainable construction methodologies. This novel method utilizes waste materials to tackle environmental and performance challenges in building.

1. Improved Thermal Comfort: MSW fly ash tiles assist in regulating interior temperatures by minimizing the temperature disparity inside structures to only 2 degrees Celsius. This little temperature variation fosters a more stable and pleasant interior atmosphere, diminishing the need for excessive heating or cooling and thereby minimizing energy use.
2. Enhanced Solar Photovoltaic (PV) Efficiency: The tiles are engineered to efficiently absorb and retain heat, hence improving the performance of integrated solar PV systems. Enhancing the thermal efficiency of the tiles substantially elevates the total energy production of the photovoltaic systems. This enhances the efficient use of solar energy, resulting in increased power output and less reliance on traditional energy sources.
3. Strategic Application of Aluminium Foil: The integration of aluminium foil on all sides of the roof tiles is essential for optimizing energy absorption. Enveloping all

four sides with aluminum foil yields a 5% increase in power production from the photovoltaic systems. Furthermore, positioning the foil in an east-west alignment increases power output by an additional 4%, and a north-south configuration yields an extra 3%. This strategic application enhances the energy-collecting efficiency of the roof tiles.

4. Sustainable Resource Management: Substituting natural sand and M sand with municipal solid waste (MSW) fly ash mitigates waste management challenges by reusing incinerated fly ash, thereby reducing the dependence on natural resources. This method facilitates the recycling and repurposing of waste resources, therefore advancing a circular economy and fostering environmental sustainability.

This strategy combines the advantages of waste material reuse with creative design to improve building performance and energy efficiency. This method incorporates MSW fly ash tiles and enhances their performance using aluminum foil, therefore minimizing the environmental effects and promoting energy-efficient building methods.

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