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Pioneering the Path to Sustainable Construction: Unveiling the Triumphs and Trajectories of Innovative Materials

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ABSTRACT

In the dynamic realm of sustainable construction, innovation in materials is a compelling strategy to overcome the limitations of conventional products. This study delves into two extraordinary case studies - Rammed Earth and Solar Pavement - to uncover their successes and potential impact. It navigates through a landscape of innovative materials, from research to real-world implementations, focusing on materials that harness nature's gifts and promote eco-consciousness, reducing carbon footprints. This investigation employs a comprehensive methodology, analysing scholarly manifestos, journal chronicles, historical documents, and credible references. It explores material identity, utility, attributes, virtues, vices, construction prowess, industry impact, journalistic coverage, ecological footprints, societal engagement, and tangible projects. Comparisons are made based on sustainability impact, economic viability, and current trends. The findings reveal that Rammed Earth stands as a sustainability luminary, leaving a minimal environmental footprint. In contrast, Solar Pavement holds intriguing promise, requiring further research, development, and audacious pilot endeavours to fully unleash its potential. This saga offers valuable insights into the strengths and weaknesses of these avant-garde materials. Armed with this knowledge, decision-makers in sustainable construction can lead us towards a harmonious future for our built environment.

1. Introduction

In the pursuit of sustainable construction practices, innovative materials have emerged as a transformative solution to address the limitations of existing products. These materials result from spontaneous ideas or systematic processes aimed at improving various criteria such as sustainability, durability, reliability, safety, cost reduction, improved quality, and environmental friendliness. The utilization of innovative materials has become a notable approach within the construction industry to achieve sustainable construction goals.

The continuous innovation of new technologies and materials plays a crucial role in achieving sustainability in construction. The use of novel materials is considered one of the key factors in this

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pursuit. A wide range of innovative materials is available in the construction industry, including combinations of natural and man-made materials such as 3D printed sandstone, bamboo reinforced concrete, bio-receptive concrete, bricks made from pollutants, plaited microbial cellulose, and superplasticizers. For the purpose of this analysis, two innovative materials have been chosen: Rammed Earth Wall and Solar Pavement. The selection was made based on their potential to benefit a global population, as well as their suitability for underdeveloped and isolated areas, where earth material and sunlight are abundant and readily available. The concept of sustainable construction evolved from the need to create a built environment that meets present demands without compromising the ability of future generations to meet their own needs. Sustainable construction emphasizes the use of recyclable and renewable resources, reduction of embodied energy in building materials, and the energy consumption of the final structure. It also involves striking a balance between social well-being, economic prosperity, the protection of the built environment, and the preservation of the natural environment.

The primary objective of this study is to identify and compare two case studies of innovative materials, Rammed Earth and Solar Pavement, and conduct a comprehensive analysis to evaluate their success and impact. Extensive research in the literature has demonstrated a wide range of innovative materials, some of which are still in the research phase while others have already been implemented in the industry. The focus is on materials that leverage the natural properties of the environment and contribute to reducing the carbon footprint, thus qualifying as sustainable materials. In conclusion, the two innovative materials under examination, Rammed Earth and Solar Pavement, exhibit distinct characteristics, strengths, and limitations. Rammed Earth construction emerges as a compelling option for those seeking building materials that foster sustainable development and minimize negative environmental impacts. On the other hand, Solar Pavement shows significant potential for future utilization; however, further research, development, and pilot projects are required to overcome its current limitations. Through a thorough examination and comparison of these innovative materials, this study aims to provide a comprehensive understanding of their effectiveness and applicability in sustainable construction practices. The findings will enable stakeholders to make informed decisions regarding material selection and implementation, thereby promoting the advancement of sustainable construction as a whole.

2. Methodology

The research method employed in this study is a comparative analysis, aiming to evaluate and compare two case studies of innovative materials in sustainable construction: Rammed Earth and Solar Pavement. The research design incorporates a comprehensive analysis of various aspects related to the materials, including their types, usage, characteristics, qualities, limitations, construction methods, industry reports, news articles, environmental impact, community engagement, social impact, and real-life project applications. To gather the necessary information and data for the analysis, a literature research approach is utilized. This involves searching for relevant scholarly writings, journals, documents, and credible online references that discuss the case studies of Rammed Earth and Solar Pavement. These sources provide valuable insights and documented experiences related to the materials, their applications, and their impacts on sustainable construction.

The research design also encompasses qualitative comparison based on sustainability impact, cost, and current trends. This involves analysing and evaluating the strengths and limitations of each material, as well as their potential for future use and development. By considering these factors, the research design aims to provide a comprehensive understanding of the effectiveness and applicability of Rammed Earth and Solar Pavement as innovative materials in sustainable construction. In this study, the focus is on innovative materials for sustainable construction, as they have gained popularity in the building industry. The characteristics and criteria of the case studies are listed and compared, along with the justification and further evaluation. Rammed Earth and Solar Pavement were chosen for comparison because they both utilize natural elements (earth and sun) as the primary sources for developing innovative materials.

The two-material comparison will provide a literature review of previous research reflecting a range of construction types, locations, and available resources. Academic articles, news articles, and industry reports on current trends will be reviewed and cited to support the comparison. Among the criteria discussed are the type, usage, characteristics, quality, limitations, and construction methods of the materials. Data on social impact (community participation), environmental impact (energy usage, carbon footprint, waste reduction), and the potential impact on the future of sustainable construction will be assessed using a qualitative approach. The key findings and recommendations regarding the use of Rammed Earth and Solar Pavement as innovative materials in sustainable construction practices will be summarized towards the end of this study.

Overall, the comparative analysis research method and design employed in this study enable a thorough evaluation and comparison of the two case studies, allowing for informed conclusions regarding the effectiveness and applicability of Rammed Earth and Solar Pavement as innovative materials in sustainable construction practices.

3. Results

3.1 Case Study 1 - Rammed Earth

Earth Construction has incited interest among researchers due to it uses a natural and readily available local materials, is easily transported to the site, and requires minimal processing, which results in low carbon emission (Mohamed Gomaa *et al.,* [25]).

3.1.1 Types

Types of earth construction available are includes rammed earth wall, light earth, adobe blocks, compressed earth blocks, and cob (Mohamed Gomaa *et al.,* [25]). The ancient well-known earth-based building material in the world is rammed earth, which is made by mixing dry soil and water before being compacted in successive lifts inside a formwork to make structures (Ciancio and Beckett, [9] & Quoc-Bao Bui & Morel [31]).

Rammed Earth known as 'pisé' in Australia (Fillip Dujardin [17]) and as 'sanhetu' in China (Alyn Griffiths [2]) is made of material consisting of one or combination of sand, gravel, clay, and silt (Quoc-Bao Bui & Morel [31]). It can be acknowledged by 2 types; 'un-stabilized' with only using existing clay as a binder (Earth Building Association of Australia [15]). It worked in moist or damp conditions before can be rammed in situ to form a wall (Ciancio and Beckett [8]). The other type is 'stabilized' with added modified binder such as cement, 'Air' lime (such as Limestone, Quicklime, Hydrated Lime, and Natural Hydraulic Lime) (Quoc-Bao Bui & Morel [31]), while some other practices are using bitumen as a binder. In achieving durability, the quantity of binder used varied from 3% to 10% (Ciancio and Beckett [8] & Earth Building Association of Australia [15]).

3.1.2 Usage

This construction is used globally in the form of either a new modern building or a heritage legacy, making it important for modern construction and maintenance work (Ciancio and Beckett [8]). On the other side, employing this type of building material also helps the community generate a consistent aesthetic, distinct personality, and sense of individuality as a whole. For population in remote area, this type of construction was derived from the need to build a shelter despite the lack of high cost, skilled labour, specialized equipment or machinery, and transportation (Johnson [20]).

3.1.3 Characteristics

Characteristic of this material are differed from one location to another. Thickness of the wall usually 300mm (Johnson [20]). This will result in the construction of sturdy, impact-resistant walls (load bearing walls) that are appropriate for both building and infrastructure work. However, the thickness depends on expected load of the structure and it can go up to 610mm (Ciancio and Beckett [8]). For structures in isolated, hot, arid places, this material can be utilized to lessen dependency on mechanical ventilation. Construction work in resource and energy-limited locations benefited from this as well. (Ciancio *et al.,* [9]).

3.1.4 Qualities

Durability and thermal is a most talk qualities that has been possess by rammed earth. Besides, it also has a good compressive strength, pullout strength, shear strength, dynamic behaviour, capacity subject to lateral wind force, hygrothermal properties, sound barrier and sensitivity to water (Earth Building Association of Australia [15]).

3.1.5 Limitation

Even though this construction is simple and straightforward (Ciancio and Beckett [8]), using rammed earth is typically labour- intensive and time-consuming (Alyn Griffiths [2]), hence, more labour is needed. For un-stabilized rammed earth, a maximum of 8% of clay binder should be used; otherwise, cracking or heaving will occur (Quoc-Bao Bui & Morel [31]). Another drawback is the challenge to regulate the internal temperature throughout prolonged seasons like summer or winter (Alyn Griffiths [2]). Moreover, if the wall wasn't well protected (stabilized), it would be susceptible to water entry, erosion, and termite infestations (Quoc-Bao Bui & Morel [31]).

3.1.6 Construction method

The procedure of this construction started with identifying locally sourced subsoil. Mohamed Gomaa *et al.,* [25] suggested, to ensure the quality of the mixture, testing should be done either on-site or in a lab before beginning the operation. Damp mixture of the subsoil should be compacted into a temporary formwork before the next layer is applied (Ciancio *et al.,* [9]). Some of other technique are using dry method where the water content limited by 10% to achieve highest dry density, before being compacted from 15mm thick of earth into 10mm thick of compacted earth inside the formwork. With the influence of drying time, this procedure will eliminate air pockets and produce high load pressure structure walls (Quoc-Bao Bui & Morel [31]).

3.1.7 Industry reports

Feedback from industry has been gained from the *First International Conference on Rammed Earth Construction* held in University of Western Australia on February, 2015. It was reported that, Modernize Rammed Earth Construction is efficient in increasing the productivity, more intricate, aesthetically attractive contemporary architecture and more versatile construction industry. However, Australia is having issues with the strict guidelines established by the Building Code of Australia (BCA) regulating the thermal evaluation of the rammed earth business. The future of this construction has been identified as being critically affected by concerns with government rules, costs, and environmental impact due to lack of standards. It was decided that design regulations contained in standards would increase the use of rammed earth by giving engineers tried-and-true design techniques. There are two sides to the rammed earth building technique: on the one hand, it can be used to create pricey architecture and award-winning structures that are featured in commercial magazines and are frequently owned by wealthy and extravagant people; on the other hand, it can be applied in developing nations and create affordable housing (Earth Building Association of Australia [15]).

3.1.8 News articles

Meanwhile, in April 4 2021, a news articles on' Beijing uncovers 3,000-year-old rammed earth construction base' has reported about a relic site (size about 700 m2) in the township of Liulihe, Fangshan District, China. This was proof that this type of building material can withstand the test of time and have the potential to be more developed for future usage (Patel *et al.,* [22]).

3.1.9 Environmental impact

In term of environment and social impact, Ciancio reported that rammed earth's superior air quality reduces dependable on mechanical cooling/heating, produced low greenhouse gas emissions, and contribute to energy efficiency. Total Production Energy comparison between Rammed Earth (0.9GJ) and Steel Frame Structure (4.4 GJ) show that 20% difference of energy saved in production of rammed earth [4]. Additionally, rammed earth homes have been shown to improve energy efficiency by reducing overall greenhouse gas emissions and carbon footprint emissions (Hengwu Hu *et al.,* [19]).

3.1.10 Community engagement and social impact

In getting community engagement and give awareness of this material, the Rammed Earth Pavilion Competition has been held in 2023 to gather ideas from worldwide designers. Among the winning design are from Switzerland, United Arab Emirates, Germany and France (Platio [23]). In Australia, efforts to engage the community have been made using skill and knowledge exchange. It was accomplished by using untrained native labourers to build with rammed earth, allowing them to return with the necessary skills and knowledge to benefit their own community and create local jobs (Ciancio *et al.,* [9]). In an effort to create a better technique and product, community feedback can also be obtained in this informal approach.

3.1.11 Project application – observation tower, Maas Valley Riverpark Nature Reserve, Belgium

Completed in 2016, this building designed by *De Gouden Liniaal Architecten and* used as a small observation tower, educational and recreational facilities.

Located on 2500 hectares area nearby Maas River at the border in between Belgium and Netherlands, it is also the first public building that used rammed earth construction in Benelux Region. Figure 1 and Figure 2. It has been erected on a small hill where Negenoord's former gravel extraction area once stood in order to provide protection from any flooding while also providing the greatest vantage point (Hengwu *et al.,* [21] & Vera Dordick [38]).

Fig. 1. Observation Tower from its exterior

Fig. 2. The ochre-rammed earth used in constructing the external wall is reinforced with a concrete core to enhance its strength

The building's layout resembles six-sided shape with opening that frame the best views. A concrete core in the middle of the tower has stairs leading up to three landings on the higher levels and out onto a rooftop terrace with a metal balcony (Material Studies Edition 2 [24]). In effort to ensure the quality of the construction and to produce mix that meet the site's condition, earth consultant and team of experts were hired to examine the local materials, combinations of mixes, as well as gathering data on mechanical characteristics and appearance (Hengwu *et al.,* [19]). This complies with Mohamed Gomaa *et al.,* [25] suggestion of doing testing before proceed with on-site construction. The workers received training in formwork building, ramming, and removal as well as mixing and maintaining the proper humidity in the mix during construction. To check on the quality, specimens were tested for compression force in the lab and for humidity in the field every week (Hengwu *et al.,* [19]).

This tower's external walls are built of rammed earth, and its inside core is made of sandblasted concrete. Combination of mix has been used are 20% gravel, 40% ochre-coloured earth and 40% clay with 'Trasslime' as stabilizer (Hengwu *et al.,* [19]). Trass lime (natural cement) is a mixture of hydraulic lime or slaked lime powder with ground trass powder (Vera Dordick [38]). This Rammed Earth construction took seven weeks to be built. Working from stair to stair, roughly 20 sqm of rammed earth were completed each week to reach the final height of about 11 meters (Hengwu *et al.,* [19]). The external Rammed Wall are made using technique of compressing layers of damp earth in moulds to form load bearing wall (Material Studies Edition 2 [24]). However gradually eroding external wall surfaces make the gravel aggregate more apparent.

3.2 Case Study 2 - Solar Pavement

Solar is a genuine natural energy that exists and has a big potential to be developed into various uses. With proper planning, the most received solar location in the world; such as the United States (U.S) would benefit from this energy as well as other countries (Selvaraju [32]). With the aim of transforming the road system from the energy consumer to the energy provider and eliminating or reducing pollution from the energy source, solar pavement is one of the options that has received the most research in developing new highway transportation infrastructures (Channi [10]). A multipurpose solar pavement is a recent solar invention that may be laid directly on top of an asphalt or cement concrete layer that already exists. A different idea is to employ a layer of solar photovoltaic power generation to replace the entire system of conventional road paving as the pavement (Channi [10]). Solar pavement also exists in the form of a landscape paving solution that makes solar technology as part of modern architecture by using recycled material for its production. This solar landscape paver technology has been developed by PlatioSolar and gained interest from various consumers (Papadimitriou *et al.,* [28]).

3.2.1 Types

Types of solar pavement has been highlighted in some of research are thermal collector and electrical collector (Yuan *et al.,* [39]). Meanwhile Hengwu *et al.,* [19] in his research are making comparison on 7 types of solar pavement from research of different scholars. The solar pavement discussed made of one or more combination of either tempered glass, solar cell, fiberglass, PMMA panel, precast concrete hollow slab, resin and glass particle coating, resin and polymer substrate, resin glass aggregate mixture, Polyurethane and glass aggregate (Channi [10]).

3.2.2 Usage

The use of this solar pavement is; to enable the decentralized expansion of renewable energy sources, prevent long power lines and energy losses, encourage the development of smart transportation and electric vehicles, effectively alleviate road ice and snow melting, reduce greenhouse gas emissions, mitigate the effects of urban heat islands, and create jobs while reducing the fuel/energy consumption of the project or nearby building (Channi [10]). Solar pavement has already been applied to parking lots, footpath, driveway and landscape area in the effort to harvest energy to be used by local houses or business that connected with the system

3.2.3 Characteristic

In general, road pavement design must adhere to certain requirements that is; surface friction, sufficient light reflective, and low sound pollution (Selvaraju [32]). Since this material will function as rigid pavement, the aim is to achieve the most durable, advanced load bearing, moisture absorption, shear loading, and other requirements from time to time (Channi [10]). Heat transfer efficiency is also a must to ensure heat accumulated on the paver surface can be transferred safely to the dedicated component (Yuan *et al.,* [39]).

The characteristic of solar pavement differs from one manufacturer to another. Generally, there are 3 layers that involved, that is 'the road surface layer', the electronic layer' and 'the base plate layer'. Some inventions are made of three-layer composite structure (transparent layer, photoelectric layer and bottom layer), some are two-layers with rubber and plexiglass panels, solar panels in-between porous rubber and there is a walkable solar photovoltaic floor tile with anti-skid toughened glass (Channi [10]). Technical assessment of several type of solar pavement has been done by Hengwu *et al.,* [19] in Table 1.

Table 1
Technical Performance Comparison of Solar Pavement manufacturer

Main technical performances for different test projects of solar pavements				
	Solar Roadways	SolaRoad	Wattway	Holow slab
Module unit size (m) (length x width x thickness)	0.66 x 0.76	2.50 x 3.50 x 0.21	1.398 x 0.69 x 0.007	0.50 x 0.50 x 0.25
Cell type	Polysilicon	Polysilicon	Polysilicon	Polysilicon
Efficiency of the Solar Pavements π_m (%)	15.6	12.1	14.8	13.2
Laying area (m^2)	41	120	2800	3
First year Generation (kWh/m^2)	70.5	78.0	53.4	34.9
Manufacturing Cost (\$/m^2)	9000-12,000	13,000-15,000	1500-2000	400-800

3.2.4 Qualities

Among good qualities of solar pavement that has been incorporated in road development are; sensor detector, road illuminator, electric vehicle charger, snow management, self-sufficient highway (embedded tracking system, electrical appliance using collected energy and high-speed internet). Besides, it is much less pollution, and no power outages. Additionally, it has the potential to provide a variety of energy conversion applications, such as traffic engineering technology, intelligent road equipment, and electric vehicle power supply, and could successfully strike a balance between the demands on the planet's finite resources and social and environmental needs (Channi [10]). This can lessen reliance on gasoline and oil while simultaneously creating temperature-sensitive heating elements to prevent snow accumulation in the winter. Moreover, this solar pavement can have a smaller negative influence on the environment by lowering the surface temperature and the amount of sensible heat discharged into the atmosphere (Katanich [13]).

3.2.5 Limitation

Hengwu *et al.,* [19] reported, the evaluation of solar pavement's bearing capacity, durability, long- term road performance, and stability of power generating efficiency currently lacks standards and test procedures (Channi [10]). Meanwhile, the deployment of solar pavement system becomes challenging as no planning to include a new solar collection tube, panel, and heat exchange equipment in the process of rehabilitating an existing road would cause long installation time (Yuan *et al.,* [39]). Unit cover for solar pavement needs to have important properties to withstand load, traction, and other road conditions, while also being transparent enough to let sunlight reach the solar panel (Katanich [13]). Hence, getting the most suitable material that fits the requirement is crucial and needs further research. Although solar energy is there all day, the amount of it varies according to sun intensity and erratic shadows cast (Selvaraju [32]). In an effort to overcome its limitation and expand the application, this solar pavement is projected to have a high starting cost and high project expenditure (Channi [10]). There are other limitations that became major concerns, such as low solar power production caused by factors like insufficient sunlight, and excess heat. Additionally, there may be issues with the ability to withstand heavy traffic loads, as well as concerns related to safety and noise (Zami *et al.,* [40])

3.2.6 Construction method

The most acceptable form of the solar pavement structure is a typical structure with functional photovoltaic, cement concrete, base, subbase, and subgrade layers [26]. The general construction method of solar pavement includes; evaluating location suitability, clearing the site, ensuring it is properly graded, and compacted, upgrading the electrical infrastructure required to connect the solar pavement system, preparing subsurface to enhance stability and drainage, installing solar panel units, interconnecting the solar panels to the electrical infrastructure, applying pavement overlay over the solar panels, finishing and testing (Waters *et al.,* [27]).

3.2.7 Industry report

As of 2021, several manufacturers have been acknowledged as among the key player in solar pavement industry. PlatioSolar is a company specializing in solar pavement systems that can be integrated into sidewalks, plazas, and other urban areas. Their solar panels are designed to be durable and withstand pedestrian traffic while generating clean energy (Papadimitriou *et al.,* [28]). *Solar Roadways* is a company known for its innovative solar panel technology designed for roadways. They have developed solar panels embedded with LED lights, heating elements, and other features to create smart and sustainable road surfaces (Waters *et al.,* [27]). *SolaRoad* is a Dutch initiative that focuses on developing solar road systems in the form of prefabricated slabs. They have created a solar bike path in the Netherlands with embedded solar panels that generate electricity from sunlight and can be used for powering streetlights, homes, or electric vehicles.

3.2.8 News articles

News on solar pavement in September 2021 with the title 'This solar-powered pavement harvests energy from under your feet' (Solar Review [35]) has talked about the innovation of using plastic waste in the making of solar pavement component. This pavement is used as a landscape paver or sidewalk paver that meant for human use. Developed by Hungarian company; 'PlatioSolar', this compacted plastic waste act as subgrade materials for the solar panel to sit on and claims to be able to withstand load of a heavy truck Figure 3. Another news in November 2021 by *2ndLookNews* entitled 'Solar Roadways: American Ingenuity to Power a Greener Future' (Business Insight [7]) wrote about the progress of turning the surface of roads into solar panels by Solar Roadways company. For conducting in-depth research on this solar pavement invention, this company has received numerous contracts from the US Department of Transportation, Department of Défense, and crowdfunding that raised USD2.2 million in 2014 and USD2.5 million in 2021.

Fig. 3. Platio Panel that is partially made from recycled waste (left) and Smart Bench with connected solar panel (right)

Figure 4 as in 2022, their Solar Road Panel (SRPs) is already in the process of reaching version. Number 5 (SR5) aimed for commercialized market. However, as January 2023, this company has yet to install an actual solar road installation (Zami *et al.,* [40]).

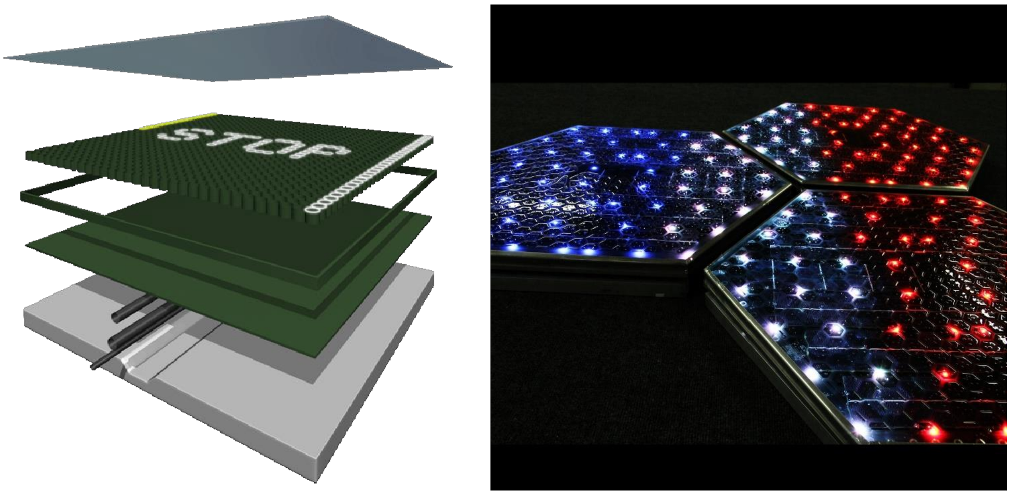

Fig. 4. *Solar Roadway* designer's conception of the very first Solar Road Panel (SR1) (left) and recent SR4 invention (right)

3.2.9 Environment impact

According to Solar Roadway, the heating plates would require 2.28 MW per lane mile while the LED lights would use 106 MWh per lane mile and the panels would produce 415 MWh. At the same time, the material used for solar pavement is made from recycled and sustainable materials (Waters *et al.,* [27]). Meanwhile, PlatioSolar reported that the equivalent of 400 PET bottles is recycled during the creation of 1 square meter of solar pavers tiles (Papadimitriou *et al.,* [28]).

3.2.10 Community engagement and social impact

Community engagement is crucial to upholding the industry's good name, minimizing opposition, addressing concerns, and fulfilling community and local government expectations for any development that has been planned. In March 2022, the Solar Energy Technologies Office (SETO) of the U.S. Department of Energy (DOE) introduced "Inclusive Solar Outreach Awards," which aim to increase equitable access to solar energy benefits and adoption, as well as to attract and retain a diverse target audience (Teh *et al.,* [37]). In Denmark community engagement also has been held to gather feedback from the community regarding future development of solar plant in that country (Asiri Design Cost of Rammed Earth Construction [3]). The criteria indicated in the two prior articles can be utilized as a guide when conducting community engagement activities for solar pavement in the future, despite the fact that no studies or articles on community engagement with solar pavement have been found for the time being.

3.2.11 Project application

Solar Review website (Zami *et al.,* [40]) reported, there are two of pilot project of solar pavement that stand out from the rest. There are;

i. WattWay, France (2016-2019): The WattWay, a solar road spanning over 0.6 miles in Normandy, France, was launched as the first of its kind and underwent real-world testing. The project was highly anticipated, with extensive plans in place to extend it to cover 620 miles of French roads. However, the WattWay did not meet the expected energy production levels and was unable to handle regular traffic, leading to an early shutdown in 2019. The CEO of the company acknowledged that the technology was not yet advanced enough for inter-urban traffic.

ii. Solar highway, China (2017-2018): The world's first solar highway was unveiled in Jinan, China in late 2017. The road spanned 0.62 miles and was praised for its innovative design. Unfortunately, the road had to be closed down just a week after its opening due to damage caused by traffic and theft. It was reported that some of the road panels were stolen. The current status of the project is uncertain.

3.3 Comparison and Evaluation – Sustainability Impact

Key principles of The Triple Bottom Line Theory are used (Sandanayake *et al.,* [36]) to evaluate the sustainability of Rammed Earth and Solar Pavement. The key principles are Social, Environment, and Economy

Table 2
Comparison and evaluation of innovative material - Rammed Earth and Solar Pavement

Sustainability Impact	Social well-being	Environmental health	Just economy
Rammed Earth	Underserved groups impacted by this goal – Native and aboriginal people in remote area, people with lower income and lack of material source [9] Barrier to more equitable outcomes - Transfer of knowledge, skills, and proper Guidelines [8]	How does the innovative material impact the below criteria; Greenhouse gas emissions -Local materials used, reduced energy and gas emission [2] Waste / pollution – No pollution expected. Waste from the construction can be recycled [8], [15] Trade-offs cost versus environmental effect - Very minimal cost incurred with low environmental impact	Local economy – Use of locally obtained materials results in a significant decrease in building costs [8] Job creation – Yes. Local job created [9], [15]. Diversity of workforce – Out-of-station labour can be used, however, there will be additional costs Tools availability for more sustainable operation – Modern equipment and machinery can be used. However, it will increase carbon footprint [31]
Solar Pavement	Underserved groups impacted by this goal – Wild animal Barrier to more equitable outcomes – To comply with road and traffic guideline, questionable practicality, vandalism, complexity of installation and maintenance [12]	How does the innovative material impact the below criteria; Greenhouse gas emissions – There was less than asphalt [39] Waste / pollution – Noise pollution is expected [40]. Plastic waste can be recycled into partial component Trade-offs cost versus environmental effect – High initial cost, high maintenance cost with average environmental impact [10]	Local economy – Electrical savings to nearby residents (with connecting electrical output) [7] Job creation – Yes [10] Diversity of workforce – Possible with more manufacturing factory Tools availability for more sustainable operation – further research and cost to overcome limitation and weakness (moisture, ice/snow, noise, safety, load, traction, et cetera) [10,40]

3.4 Comparison and Evaluation – Cost Effective

Overall, the assessment suggests that both technologies need further development and cost optimization to become truly viable alternatives on a large scale. Rammed earth holds promise for its low environmental impact, but its implementation requires addressing specialized skill requirements and uncertainties in industrial-scale costs. Solar pavement, while potentially generating energy, faces challenges in cost-effectiveness and recouping its installation expenses. Therefore, further research and development are crucial to overcome these limitations and unlock the full potential of these technologies for sustainable infrastructure development.

Table 3
Analysing the cost-effectiveness of Rammed Earth and Solar Pavement

Criteria	Rammed Earth	Solar Pavement
Initial cost ($/m2)	The average initial cost of a rammed earth wall is about $8.63/m2 to $22.50/m2 [3]	Solar Roadway ($10,500), SolaRoad ($14,000), Wattway ($1,750), Hollow slab ($600) [20]. Lowest initial cost evaluated is $252/m2 [30]
Levelized Cost of Energy ($/kWh) -	No information	Solar Roadway ($3.46), SolaRoad ($5.92), Wattway ($0.61), Hollow slab ($0.23) [10]
Nett Present Value ($/m2)	No information	Solar Roadway ($14,713), SolaRoad ($19,617), Wattway ($2,452), Hollow slab (841) [10]
Manufacturing cost ($/m2)	USD $ 330.26/m2 (based on the Unit Price Analysis) USD $280.72/m2 up to $379.80/m2 Both figures from the resource	Solar Roadway ($9,000 – $12,000), SolaRoad ($13,000-$15,000), Wattway ($1,500-$2,000), Hollow slab ($400-$800) [10]
Cost efficiency (%)	No information	Ranging between 12.1% and 15.6% . [10] The percentage is low, hence not efficient
Evaluation	Even though soil sourced on-site can reduce transportation costs [8], other considerations should be taken into account such as specialized expertise, the machinery, labour, price of building additives, and the transportation of finished goods to the construction site [40]. Because rammed earth has a far lower embodied energy than other widely used construction techniques now on the market, it seems promising to be applied [2].	Although there are some pilot projects, the cost does not represent the cost of installing roads on an industrial scale. When compared to thermal collector pavement, Papadimitriou *et al.,* [29] claimed that electrical collector pavement is more expensive [28] Benefits deriving from the solar pavements are not enough to cover the cost during 20 years of a lifetime [10,40].

3.5 Comparison and Evaluation – Current Trend

Both rammed earth and solar pavement offer promising potential for sustainable infrastructure development, but they face different challenges and are at different stages of maturity.

i. Rammed earth is closer to widespread adoption due to its lower environmental impact and established construction techniques. However, cost and skill limitations currently hinder its broader use.
ii. Solar pavement is a more futuristic technology with exciting possibilities for renewable energy generation and urban heat mitigation. However, its high costs, limited energy generation, and unknown long-term performance require further research and development before it can be widely implemented.

The choice between these technologies depends on specific project needs, priorities, and context. Rammed earth may be a better choice for projects focused on environmental sustainability and low embodied energy, while solar pavement may be more suitable for areas seeking renewable energy generation and urban heat mitigation.

Ultimately, both technologies have the potential to contribute to a more sustainable future for our cities and infrastructure. Continued research, development, and innovation will be crucial to overcome current challenges and unlock their full potential.

Table 4
Assessing and contrasting the prevailing tendencies in Rammed Earth and Solar Pavement

Criteria	Rammed Earth	Solar Pavement
Current Trends	Automated construction by using robotic arm as compactor, using Pneumatic Tamper to ram the earth, Prefabricated Panel of earth block, developing Modern Formwork, 3D printing, automated machine [25]. Using one of the three pieces of BCA accredited software (NatHERS, 2012) to calculates a 'star rating' for the building, to maintain comfortable indoor temperature and 'AccuRate' software [9] The seismic standard has been taken into consideration when deciding guidelines for rammed earth construction [5,20].	An integrated solar pavement that harvests thermal energy from the sun as well as sunlight and uses a thermoelectric generator to convert it to electrical energy [28]. In 2022, there is also research into utilizing solar panel waste used along the roadside to be included in pavement construction [36]. However, future studies should be done to investigate the compatibility of pavement materials with waste. In the effort to overcome high urban temperatures, the Road Pavement Solar Collector System has been studied to evaluate its impact of absorbing heat from the road surface and converting it into passive thermal energy [12].
Evaluation	This development will offer high economic and environmental benefits due to reduction in labour, construction time, and formwork	Generally, solar pavement technology has been tested for only a small number of applications. It is unclear what the ongoing maintenance liabilities may be as the technology ages over time

4. Conclusions

In conclusion, the comparative analysis of Rammed Earth and Solar Pavement reveals distinct characteristics, benefits, and limitations for each material. Based on the analysis of literature and case studies, the following main conclusions can be drawn:

i. Rammed Earth construction is a simple technology that utilizes local elements and requires minimal steps to construct. This results in a lower carbon footprint, reduced negative impact, and a more sustainable environment.
ii. Solar Pavement, on the other hand, necessitates a higher level of expertise and reliance on technology for manufacturing and installation. Long-term investment in resources is required, which can increase the carbon impact.
iii. Both materials have their own strengths and limitations. Feasibility studies should be conducted to assess the suitability of their development before implementation.
iv. Rammed Earth construction has a long history of use, but progress in terms of improvements and modifications has been limited.
v. Solar Pavement is still in its early stages, with pilot projects underway. There is ample research, grants, and potential for modifications in this field.
vi. The economic benefits of rammed earth construction lack sufficient evidence, despite the potential for low-cost construction mentioned in most studies.
vii. Economic benefit studies on solar pavement have been conducted using four companies as case studies. The findings suggest that the current cost benefits derived from solar pavements are not enough to cover the expenses over the 20-year lifespan. However, it can be economically attractive if the Levelized Cost of Energy (LCOE) is lower than 0.2 $/kWh.
viii. For rammed earth construction to gain widespread adoption, challenges need to be addressed, such as the preference for buildings with more complex geometry. Further

exploration of formwork connections is necessary, and the material requires code and guideline development in areas such as strength and thermal requirements.

ix. Solar pavement should be thoroughly examined in terms of design and material considerations to ensure compliance with road safety guidelines. Additionally, the system's overall longevity needs to be carefully considered to reduce future maintenance costs and prevent deterioration over time.

Rammed Earth construction appears to be the preferable option for sustainable development and minimizing negative environmental impact. However, solar pavement holds potential for future use, requiring additional research, development, and pilot projects to overcome its limitations. Based on the comparative analysis of Rammed Earth and Solar Pavement in sustainable construction, the following recommendations can be made:

i. **Further Research and Development:** Both Rammed Earth and Solar Pavement should continue to be the focus of research and development efforts. This includes exploring ways to improve the strength, durability, and thermal performance of rammed earth construction. For solar pavement, advancements should be made in terms of cost-effectiveness, efficiency, and longevity.
ii. **Pilot Projects and Case Studies:** Conducting more pilot projects and case studies for both materials will provide valuable insights and practical experiences. These projects can help identify challenges, refine construction techniques, and assess the long-term performance of the materials in different environments.
iii. **Collaboration and Knowledge Sharing:** Encouraging collaboration and knowledge sharing among researchers, professionals, and stakeholders in the field of sustainable construction is essential. This can be done through conferences, workshops, and online platforms, enabling the exchange of ideas, best practices, and lessons learned.
iv. **Regulatory Framework and Guidelines:** Developing comprehensive regulatory frameworks and guidelines for both Rammed Earth and Solar Pavement will promote their wider adoption. These frameworks should address aspects such as structural requirements, thermal performance, safety standards, and construction practices. Clear guidelines will help ensure quality control, enhance public trust, and facilitate the integration of these materials into building codes.

By implementing these recommendations, the construction industry can further explore and harness the potential of Rammed Earth and Solar Pavement as sustainable building materials, contributing to a greener and more environmentally friendly built environment.

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