Appendix S

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Research and Development of Solar PV Pavement Panels for Application on the Green Deck

(Final Report)

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Summary of Green Deck research project (Prepared by Prof. Yang Hong-xing, BSE)

Research and development of solar PV pavement for application on the Green Deck

Our previous study demonstrates that the available roof and vertical facade area for PV installation is very limited due to green areas and other facilities on the Deck. To explore more possible areas for solar power generation, the walkable solar PV floor tile is proposed for installation on pavements and cycling tracks, which receive a lot of sunshine every day. The feasibility and potential area of applying this innovative PV floor on the green deck was investigated. We purchased raw materials and developed two solar PV floor tile prototypes, and conducted laboratory tests and outdoor tests to evaluate its electrical, thermal and mechanical performance. Results show that the developed PV floor can achieve satisfactory performance in solar energy conversion efficiency, anti-slip, heat-resistance, durability and compressive strength, demonstrating that such PV floor tiles can be used as a replacement of the pavements and cycling tracks in the Green Deck. Such PV floor can combine active elements (power generation) with passive elements (waste material for back panel manufacture), providing an innovative and green solution to integrate sustainable energy technologies into the deck and to achieve the target of zero energy consumption (zero GHG emissions) of the deck. Although this project is completed, we will pursue this study and develop more eco-PV floor tiles by introducing the eco-glass block as the rear support layer through collaboration with Prof C S Poon in CEE department.

1. Introduction

Hong Kong, locating at a lower latitude area, is suitable for solar energy application, especially building-integrated solar photovoltaic (BIPV) application for power generation in urban environment. A BIPV system is highly dependent on available installation area of a building because usually the PV panels are placed on roofs or vertical facade of a building due to their broad and open surfaces for receiving more sunlight. However, in the proposed Green Deck project, our previous study demonstrates that the available roof and vertical facade area for PV installation is very limited due to green areas and other facilities on the Deck [1]. To find more possible areas for solar power generation, this research project has focused on how to use the pavements and cycling tracks for installing PV panels so that most or all the electricity consumed by the Deck can be supplied by solar energy. Therefore, walkable solar PV-panelled pavement is proposed to replace traditional floor tiles for the pavements and cycling tracks, which receive a lot of sunshine every day. This is a green and innovative solution to integrate sustainable energy technology into the deck and to achieve the target of zero energy consumption and zero greenhouse gas emissions of the Green Deck. Moreover, the appealing design of the solar pavement could offer a fantastic range of configuration possibilities in colour to enhance the aesthetic value.

The major objectives of this study area as follows:

1) to investigate the feasibility of this technology on the Green Deck;
2) to develop new PV floor tiles used for pavement;
3) to study the panels' electrical, thermal and mechanical performance theoretically and experimentally, and
4) to compare the performance of the developed and purchased PV floor tiles.

2. Literature review on similar technologies in the world

Currently, there are several demonstration projects of solar road or pavement in the word. The Netherlands built the world's first solar road, which is an energy-harvesting bike path paved with glass-coated solar panel (Figure 1). After one-year's trial, the novel solar road has proved more successful than expected [2]. It can generate about 70kWh/m^2/year, indicating that the 70-metre test bike path is enough to power a small household. However, this cutting edge technology is under its infant development stage and still has some problems. Such solar panel is very heavy so it is very difficult to install it. Besides, the anti-slip coating, which provides grip to the surface, has become delaminated due to long term sun exposure and temperature fluctuations.

Figure 1 Netherlands' solar road project

Another innovative technology is the walkable solar PV pavement developed by Spanish tech company Onyx Solar [3]. Such PV floor can comply with the anti-slip regulation and support 400 kg in point load tests. To demonstrate the capabilities of the technology, The George Washington University created what is claimed to be "the first walkable solar-panelled pathway in the world" (Figure 2). This micro power plant has a peak power output of 400 watts, which is enough to illuminate an array of 450 LEDs that light the pathway at night, shining up through the panels from beneath. However, this solar cell is based on amorphous silicon technology with relative low efficiency. Besides, the front glass is translucent so the received solar radiation is reduced. Therefore, the power output is very limited.

Figure 2 A walkable PV pavement system

The third technology is the solar block or solar brick light (Figure 3), which are integrated with a self-contained illuminating device. They can add both day and night-time colour to walkways and other outdoor surfaces without additional wiring. The small PV tiles can generate electricity and store energy (even in rainy days), emitting a soft LED glow at night. This technology is popularly used in some parks and walkways. However, the major problem is that each PV tile can only generate several watts electricity for powering LED lights, not suitable for large scale power generation system.

Figure 3 Solar PV light emitting tiles

3. Development of PV pavement prototype

In order to develop our new product from this project, we developed a new type of solar PV payment panel through collaboration with a local solar PV engineering company. Figure 4 shows the layout design of the PV floor configuration, which is sandwiched between anti-slip front tempered glass, EVA/PVB foils, solar cells, and rear support tempered glass. The total front size is 500×500mm, similar to the general pavement tiles. The thickness is about 20mm. In each floor tile, 9 monocrystalline silicon solar cells are connected in series, so that he expected power generation and efficiency are about 30-40Wp and 15%, respectively.

3.1. PV floor configuration and sample

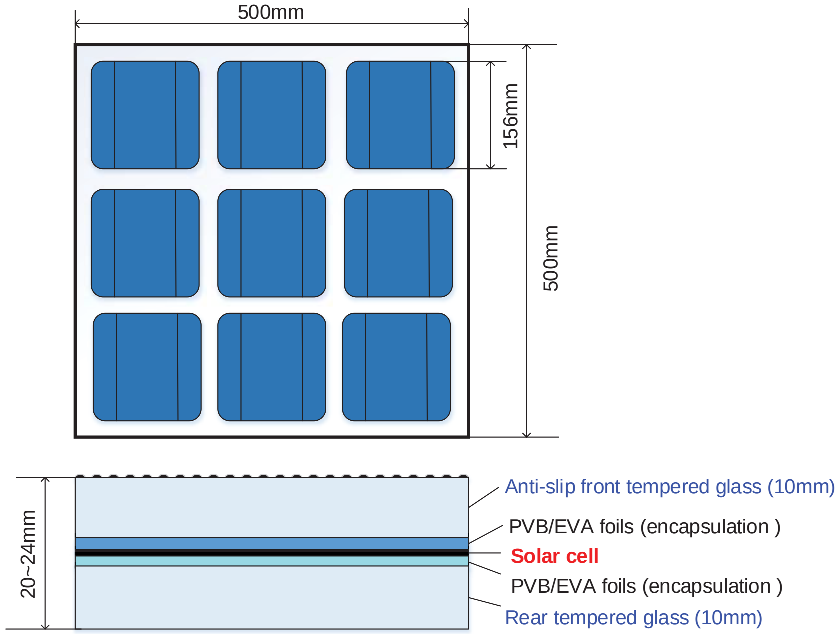

Figure 4 PV floor tile configuration

Figure 5 PV floor tiles with different anti-slip surfaces

The raw materials including tempered glass and solar cells were purchased from manufacturers in mainland China, and then they are laminated in a local company in Hong Kong (Eco Engineering Limited). Figure 5 shows the two developed prototypes of the PV floor tiles with different anti-slip surfaces, i.e. cross-line pattern and dot pattern. In general, the floor tile with cross-line layer has higher anti-slip performance but lower sunlight transmissivity.

3.2. Major features

The major features of the developed solar PV floor tile are summarized in **Error! Not a valid bookmark self-reference.**. Most of the data was provided by the manufacturers of the tempered glass and solar cell. The static coefficient of friction of the PV floor is higher than the suggested values in Chinese National Standard, indicating that it has high anti-slip performance. It also has high transparency with solar light transmissivity of 90%. The heat-resistance temperature can be up to 288 ºC, so there is no need to worry about whether it will be broken under long time sun exposure. The energy efficiency of solar cell and module can be up to 18% and 15%, respectively.

Table 1 Major features of the developed solar PV floor tile

Features	**Parameters**
Anti-slip	Static coefficient of friction (COF): 0.78 for dry surface 0.54 for wet surface GB COF≥0.5
High efficiency	module: 15%
High transparency	transmissivity: 90%
High compressive strength	max load: 74 kpa
High heat-resistance temperature	up to 288 ºC

3.3. Electrical and thermal performance evaluation

(1) Indoor laboratory test

The test of the developed PV floor tile was first conducted in our solar simulator laboratory (ZN1013). Figure 6 shows the test rig. The instrument EKO MP-11 is used to collect the I-V curve and power output every minute. The pyranometer is used to measure solar radiation intensity at the same level with the PV floor tile.

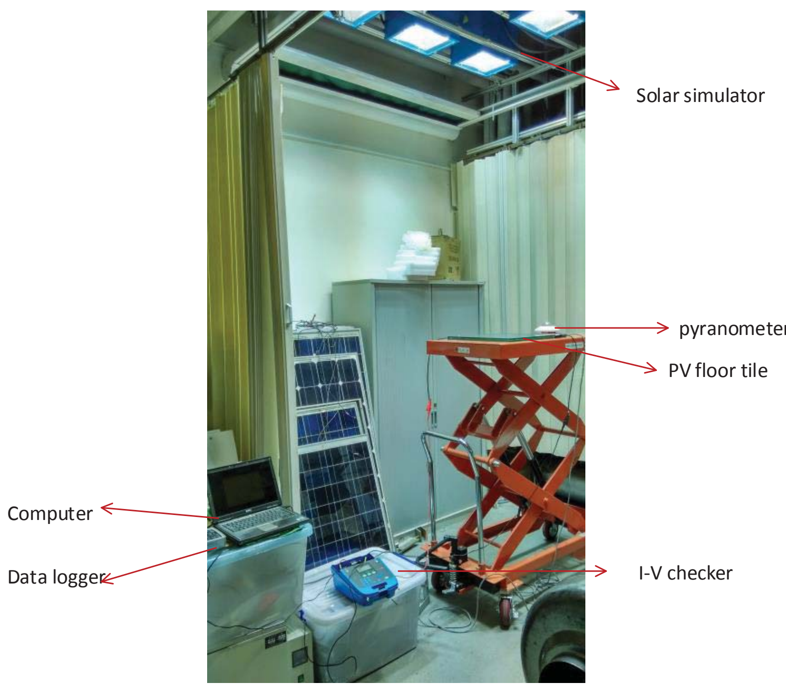

Figure 6 Test rig in PolyU laboratory (indoor test)

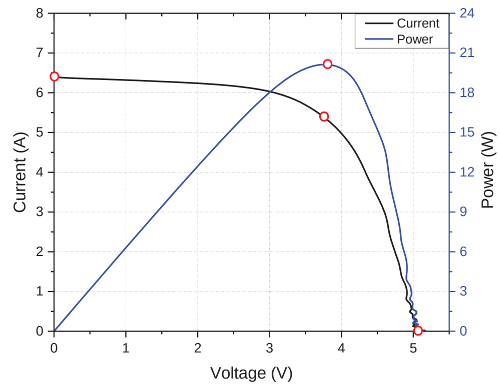

Figure 7 An example of the collected I-V curves and P-V curves

Figure 7 shows an example of the collected I-V curves and P-V curves. Table 2 gives some typical characteristic data. It can be observed that the maximum power output is 20.5W when solar radiation is 960W/m^2, and the energy efficiency is 10%.

Table 2 Data summary of the collected example I-V curve

Parameter	Value
Test Date	10/28/2015
Test Time	11:35:00 AM
Irradiance:[W/m^2]	890
Module Temperature:[℃]	56
Maximum Power: Pmax[W]	**20.5**
Open Circuit Voltage: Voc[V]	5.05
Short Circuit Current: Isc[A]	6.42
Maximum Power Point Voltage: Vpm[V]	3.7
Maximum Power Point Current: Ipm[A]	5.53
Fill Factor: FF	63%
Eta: η	9.2%

(2) Outdoor test

We also conducted outdoor tests on the solar PV floor on the 6th floor of Bock Z with an open and no shaded space (Figure 9). The electrical and thermal performance has been tested. Figure 9 illustrates the collected solar radiation and power output from 12:00 to 3:00 in the afternoon. It is obvious that the variation of power output has close relationship with solar radiation. Besides, the solar radiation on the day is not very good because the weather is cloudy, ranging from 200 to 800w/m^2, therefore the power output of one PV floor tile is from 5 to 20W, and resultant efficiency is about 10%.

Figure 8 Outdoor test system in the 6th floor of Block Z

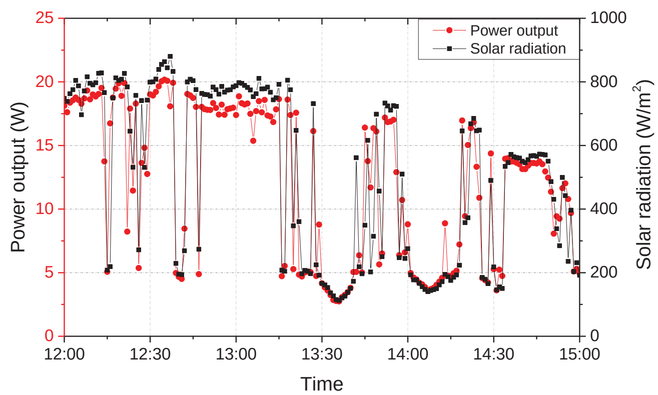

Figure 9 Collected solar radiation and power output

The temperature of the PV floor tile under outdoor test was measured to evaluate its thermal performance. Figure 10 presents the temperature profile of the back side of PV floor tile. The module temperature is in the range of 40-50 ºC although the ambient temperature is about 25ºC on that day. Based on the specification of solar cell, the high temperature will have negative impact on power output by -0.5%/ºC, therefore, the temperature difference of 25~30ºC can result in about 13% (4W) decrease in power output.

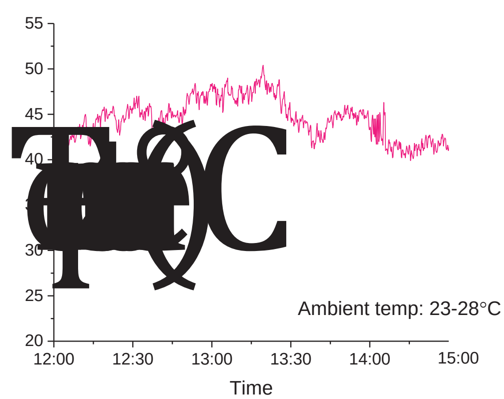

Figure 10 Thermal profile of the PV floor

The laboratory test and outdoor test results show that the power output are lower than the rated values because the transmissivity of the tempered glass is reduced by the additional anti-slip surface, which means that the received solar radiation on solar cells is decreased and the measured temperature of the PV floor is very high, which can reduce power generation by 10%-20%. Besides, the solar radiation on that day fluctuates greatly and does not reach the standard test condition of 1000W/m^2.

3.4. Mechanical performance evaluation

The mechanical performance was tested in the Structural Engineering Research Laboratory with the help from Prof. C S Poon and Dr. Eddie Lam in CEE Department. As shown in Figure 11, the force is added gradually through the load cell. When the PV floor is damaged, the maximum load and compressive strength can be calculated.

Figure 11 Compressive strength and durability test of PV floor tile

Figure 12 shows the PV floor tiles after damage. We can see that both of the two tiles are damaged at the back side. Even though the glass is broken, it still a completed tile and does not fly to pieces. Therefore, it could be safe if it is broken due to some external reasons. It is strange that the solar cells are not damaged and can still generate electricity even though the glass is damaged.

Figure 13 shows the test process of adding load on PV floor tiles. The maxim compressive strength for samples #1 and sample #2 are 15.4 MPa and 16.2MPa, indicating that the developed solar PV floor tile has very high mechanical strength and durability. As reference, the compressive strength of concrete tile is usually in the range of 20-50MPa, indicating that the mechanical strength of the PV floor tile is close to concrete.

Table 3 lists some example ground pressure values from humans, bicycles and cars. All of them are in the scale of kPa, much smaller than the compressive strength of the PV floor, indicating that there is no problem for people, bicycles, even cars passing through the floor tiles.

Figure 12 PV floor tiles after damage

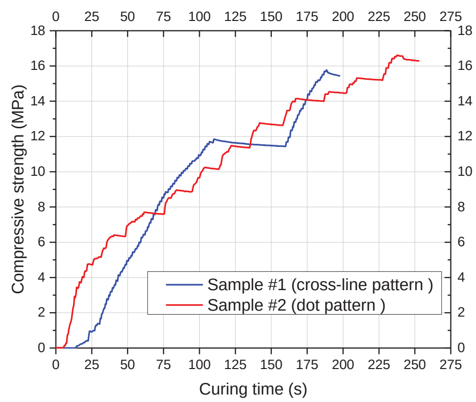

Figure 13 Compressive strength of the two developed PV floor tiles (durability performance)

Table 3 Example ground pressures values [4]

Example Ground Pressures Values	
Human	5-50kPa
Road racing bicycle	620kPa
Mountain bicycle	245kPa
Passenger car	205kPa

4. Available product in the market

While we developed our own products, we also purchased a sample walkable PV floor tile available in the market. This product, developed by a Spanish company Onyx, has been applied in the demonstration project in George Washington University. We contacted a local distributor, Jebsen Building Products Limited, for this product. The cost of one sample is HK$6,790. **Error! Not a valid bookmark self-reference.** shows the detailed technical data including electrical and mechanical parameters.

Table 4 Technical specifications of Onyx PV glass floor [5]

Photovoltaic Glass cell type	a-Si Thin Film		**Mechanical description**		
Electrical Data test conditions (STC)			Area	600x600	mm
Nominal peak power	**22.11**	Pmpp(W)	Thickness	16.72	mm
Open-Circuit Voltage	45.35	Vac (V)	Transparency	0%	%
Short-circuit current	0.72	Isc (A)	Front glass	6	mm anti-slip glass
Voltage nominal power	34.02	Vmpp(V)	PV glass	3.2	mm float glass
Current nominal power	0.65	Impp(A)	Rear glass	6	mm tempered glass
Power tolerance (not >)	±5	%	encapsulation	1.52	mm PVB Foils

The electrical performance of the PV floor has been tested. An example of the collected I-V curves are presented in Figure 14. The maximum power output at the solar radiation intensity of 1194W/m^2 is 28.6W, which is equivalent to 22.1W when solar radiation intensity is converted to standard test condition. Because such floor tile is made of amorphous silicon solar cells, the solar energy conversion efficiency is only 6.1%, which is much lower than the prototype developed by our group (over 10%). The efficiency may be further reduced if they are placed in real condition due to the influence of high floor temperature.

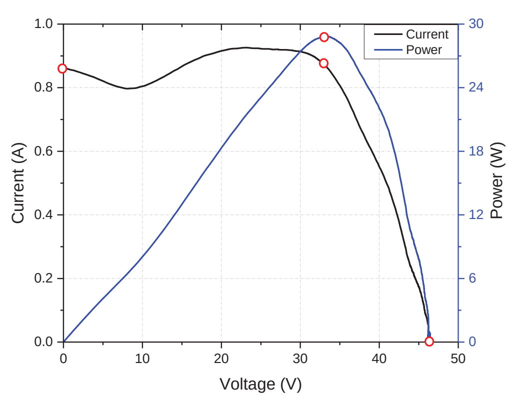

Figure 14 An example I-V and P-V curve

5. Evaluation of potential installation area and power generation

A PV system is highly dependent on the available installation area. In our previous report, the roofs of the Hong Kong Coliseum and the university buildings in PolyU campus are proposed for PV installation, but these areas are not within the Green Deck boundary. Therefore, only the walkways and other constructions, such as sports complex and art gallery can be installed with solar panels. The walkways on this deck can be one of the major contributors for PV installation, using the developed solar PV floor technology.

Figure 15 Potential PV pavement installation area on the Green Deck

As presented in **Error! Reference source not found.**, based on our calculation using CAD software, an estimation of about 5500m^2, 12.8% of the total deck area, can be used for PV floor installation. Such PV installation can generate 550,000 kWh per year, accounting for about 26% of the total electricity consumption of the Green Deck. If the new roofs and vertical facades of the hotels and other buildings within the Green Deck are counted for PV panel installation, there is no doubt that 100% of electricity will be generated from solar panels in the Green Deck, i.e. zero carbon emission will be achieved from the new development.

6. Future study

Although this project is completed, we will continue this study to develop innovative solar PV pavement panels for sustainable urban development. A whole lifecycle analysis, including the economic cost, payback time, CO_2 reduction potential, will be carried out. We will also collaborate with Prof. C S Poon in CEE department to further develop the PV floor tiles. As shown in Figure 16, the original rear PV glass will be replaced with eco-glass block [6], which is developed by Prof. Poon with recycled concrete and glass, to increase the rate of re-utilizing of waste glass in Hong Kong. We will develop more eco-PV floor tile samples and conduct a long-term outdoor testing campaign on their electrical and thermal performance. Finally, we will submit a patent application for this novel technology.

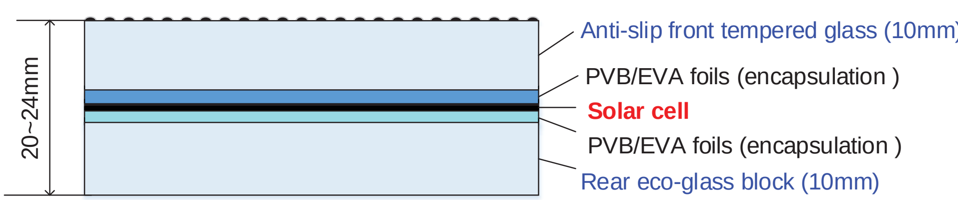

Figure 16 Configuration of PV floor integrated with recycled eco-glass

7. Conclusions

In this study, the walkable solar PV floor tile is proposed for installation on pavements and cycling tracks for the Green Deck project. The feasibility and potential area of applying this innovative PV floor on the green deck was investigated. We purchased raw materials and developed two solar PV floor tile prototypes, and conducted laboratory tests and outdoor tests to evaluate its electrical, thermal and mechanical performance. Results show that the developed PV floor can achieve satisfactory performance in solar energy conversion efficiency, anti-slip, heat-resistance, durability and compressive strength, demonstrating that such PV floor tiles can be used as a replacement of the pavements and cycling tracks in the Green Deck. Such PV floor can combine active elements (power generation) with passive elements (waste material for back panel manufacture), providing an innovative and green solution to integrate sustainable energy technologies into the deck and to achieve the target of zero energy consumption (zero GHG emissions) of the deck. Although this project is completed, we will pursue this study and develop more eco-PV floor tiles by introducing the eco-glass block as the rear support layer through collaboration with Prof C S Poon.

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