Development of structure model of hollow slab for solar pavement based on light-guide concrete

X D Zha¹, H W Hu¹, Z W Wang¹, H P Chen¹ and C J Zhang¹

¹School of Traffic and Transportation Engineering, Changsha University of Science and Technology, Changsha 410114, Hunan, China

Corresponding author: 993561963@qq.com

Abstract. To develop a reasonable structure type of solar pavement, a kind of structure model of hollow slab was proposed for solar pavement based on light-guide concrete in this paper. It is composed of two parts: a rectangular hollow slab of light-guide concrete with an arch chamber as well as a solar panel which is installed in the arch chamber. Each light-guide body is compounded of a convex lens, a prism and a light-guide fiber. Through building a three-dimensional finite element model for the pavement structure of hollow slab, the mechanical responses of hollow slab were numerically simulated, thus the geometric sizes of arch chamber were optimized according to the requirements of bearing capacity. By establishing a simulation analysis model of light path for the light-guide body, the total solar energy of single day transmission for the light-guide body were numerically simulated, then the geometric sizes and optical parameters of light-guide body were optimized according to the condensing and light-guide performances. Accordingly, the steel shaping die was designed and manufactured, and the hollow slab model of light-guide concrete was prepared by taking self-compacting concrete as slab matrix. The mechanical properties and the power generation efficiencies were tested for the model. The results show that the developed hollow slab of solar pavement based on light-guide concrete has high strength, and its working voltage and maximum output power increase with the increase of the number of light-guide bodies. Therefore, the model can meet the dual function requirements of safe driving and clean power generation.

1. Introduction

Solar pavement is a kind of pavement structure which paves a surface layer of power generation with photovoltaic solar cells on new or existing pavement. It can achieve the purpose of clean power generation on the basis of satisfying the normal traffic function to provide the power support for smart transportation. This idea was first put forward by S. Brusaw and his wife in 2006, and named as “Solar Roadways” or “Intelligent Highway”. In March 2014, they built the world’s first prototype solar parking lot, and the structure of newly designed SR3 is a hexagonal solar road panel with “upper and lower float glass panels + middle solar cells” [1]. In 2014, A. B. Northmore et al. developed a kind of solar road panel in combination with Canadian traffic and environmental conditions, and the structure is an aluminum frame rectangular panel with “tempered glass panel + solar cells + fiberglass base panel” [2-3]. In November 2014, the world’s first bike road with integrated solar panels was built in Netherlands, and named as “SolaRoad”. The SolaRoad section is 70 m long and 1.7 m wide, which is a rectangular plate with the structure of “tempered glass panel + solar panels + concrete slab” [4]. In December 2016, the world’s first solar paneled road with 1 km long was constructed in France, and named as “Wattway”. The Wattway structure is a rectangular plate with “silicone resin coating + solar...
cells + polymer base panel” [5]. In 2017, A. S. Dezfooli et al. designed two prototypes entitled as “solar panel” (solar cell embedded in rubber and Plexiglas) and “solar pavement” (solar cell embedded between two porous rubber layers) [6]. In December 2017, China built the world’s first expressway with solar pavement of 1080 m long on Jinan Ring Expressway of G2001 in Shandong Province, and named as “photovoltaic pavement”. The structure is a rectangular plate of “tempered glass particle resin concrete + monocristalline silicon photovoltaic panels + fiberglass polymer base panel” [7].

Overall, the researches on solar pavement at home and abroad are still in the exploratory stage at present. Most of existing researches adopted the rectangular or hexagonal solid panel structures, which are composed of three layers: a surface layer with transparency and skid resistance, a middle layer with photovoltaic cell and a bottom layer with water insulation and protection. However, because the solar pavement is obviously different from the traditional pavement in structure design, material property and construction technology as well as bearing capacity, pavement performance, power generation efficiency, durability and engineering cost etc., new structure types need to be further explored. Therefore, in 2010, we designed and prepared a kind of hollow slab structure which can protect solar cells [8-9], and further proposed a hollow slab structure of solar pavement based on light-guide concrete [10]. In this paper, the structure model was developed to provide a reference for the exploration of solar pavement.

2. Structure design and simulation analysis of hollow slab for solar pavement of light-guide concrete

2.1. Structure design

The hollow slab structure of solar pavement based on light-guide concrete is mainly composed of two parts: a rectangular hollow slab of light-guide concrete and a solar panel, as shown in figure 1. Wherein, the inner cavity of hollow slab adopts an arch chamber structure with parabolic vault, the solar panel is installed in it, and the slab matrix is made of self-compacting concrete. Each light-guide body is compounded of a condensing lens (compounding of a planoconvex lens and a truncated cone-shaped prism) and a cylindrical light-guide fiber, as shown in figure 2. The light-guide bodies are arranged in the hollow slab at equal intervals according to the chessboard style. The convex lens are installed on the surface of hollow slab as the light entrance end, and the light exit end of light-guide fiber is placed at the vault of arch chamber. The working principle of the structure is that: when the sunlight irradiates on the hollow slab surface, the solar rays are condensed, guided and projected onto the solar panel through the light-guide bodies, thereby the light energy is converted into the electric energy reserves by the photoelectric effect.

Where in figure 1, L, B and H are the length, width and height of hollow slab, respectively; h, l, t and h are the arch width, floor thickness, arch height and roof thickness of arch chamber, respectively, and that is $H = l + t + h$. Where in figure 2, d and r are the thickness and lower circular surface radius of planoconvex lens, respectively; a is the radius of light-guide fiber, the fiber can be appropriately bent, and its length can be adjusted according to its layout location in the hollow slab; c is the height of truncated cone-shaped prism, and the prism combines the planoconvex lens and the light-guide fiber into a whole, so that its upper and lower surfaces are separately connected with the lower circular surface of planoconvex lens and the top circular surface of light-guide fiber, i.e. its corresponding upper and lower surface radius are r and a, respectively; N is the refractive index of condensing lens; R and F are the upper spherical radius and focal length of planoconvex lens, respectively.

It can be seen that the structure has the following characteristics:
1) The concrete slab has sufficient bearing capacity, and the arch chamber can reduce the tensile stress of hollow slab concrete at the vault to meet the requirements of traffic load.
2) The spherical surface of condensing lens are exposed on the slab surface, and it is similar to the prompting blind road, which can improve the surface skid and wear resistance.
3) The solar panel is installed in the arch chamber, which can be obtained effective protection to avoid direct bearing and fracturing failure, and avoid overheating to reduce power generation efficiency.
4) The light-guide body has the function of condensing solar rays, which can improve the power generation efficiency of solar panel and reduce the number or size of panel.

5) The electronic components and connecting wires etc. can be installed in the arch chamber to meet the waterproof requirements.

6) The slabs are convenient in splicing and maintenance, appropriate in cost, and can be formed the solar power generation system. Therefore, the structure can meet the dual function requirements of safe driving and clean power generation.

\[\text{Figure 1. Hollow slab structure of solar pavement based on light-guide concrete}\]
\[\text{Figure 2. Elevation view of structure for light-guide body}\]

2.2. Mechanical analysis of pavement structure of hollow slab

In order to determine the reasonable sizes of arch chamber, the three-dimensional finite element method was used for the numerical simulation in accordance with the hollow slab structure in figure 1. The whole pavement structure is regarded as a single hollow slab structure on linear elastic homogeneous foundation with the complete bonding between the layers and without counting the dead weight. The full constraints are applied to the bottom surface of foundation, and the horizontal displacement constraints are applied to the surrounding sides of foundation. The hollow slab is a plate with four free edges. The standard axle load of BZZ-100 is adopted and equivalent to the vertical uniformly distributed load of double-wheel rectangle of 18.6 cm × 19.2 cm with the contact pressure of 0.7 MPa, the double-wheel center distance of 31.4 cm and the total width of 50.0 cm.

According to our existing analysis results [8-10], both the length and width of hollow slab were taken as 50 cm, and both the length and width of foundation were taken as 3.5 m with the thickness of 5 m. Meanwhile, the worst loading position is that the double-wheel load is symmetrically arranged on the arch chamber of hollow slab. Considering the symmetries of structure and load, the quarter model was chosen to build the solid structure model, as shown in figure 3. Wherein, the solid element model was adopted as the SOLID65 element, and the interlayer contact was adopted as the surface-surface contact model. The mesh size of hollow slab was taken as 1 cm, and the mesh sizes of foundation were gradually increased from shallow to deep and from near to far.

On the basis of keeping the plane size of hollow slab unchanged at 50 cm × 50 cm, the value-taking schemes of geometric parameters of arch chamber were selected in table 1. The elastic moduli of concrete and foundation are $E_c = 31$ GPa and $E_b = 200$ MPa, and the Poisson’s ratios are $\mu_c = 0.15$ and $\mu_b = 0.30$, respectively.
Figure 3. Three-dimensional finite element modelling for pavement structure of hollow slab

Table 1. Value-taking schemes of geometric parameters of arch chamber

| Scheme | Arch width (b cm) | Floor thickness (l cm) | Arch height (t cm) | Roof thickness (h cm) |
|--------|------------------|-----------------------|-------------------|----------------------|
| 1      | 20               | 5.0                   | 5.0               | 5.0                  |
| 2      | 22               | 5.5                   | 5.5               | 5.5                  |
| 3      | 24               | 6.0                   | 6.0               | 6.0                  |
| 4      | 26               | 6.5                   | 6.5               | 6.5                  |
| 5      | 28               | 7.0                   | 7.0*              | 7.0                  |
| 6      | 30               | 7.5                   | 7.5               | 7.5                  |
| 7      | 32               | 8.0*                  | 8.0               | 8.0*                 |

The ANSYS software was used for the numerical simulation. The influence laws of various geometric parameter changes of arch chamber on the mechanical responses of pavement structure of hollow slab were analyzed in the order of \( b \rightarrow l \rightarrow t \rightarrow h \), and the appropriate values of each parameter were determined separately. Among them, when a certain parameter change will be analyzed, its values are selected separately according to each schemes in table 1. The previously determined parameters are chosen according to the determined values, and the subsequently undetermined parameters are taken according to the schemes with "*" in table 1. It can be obtained by numerical simulation that the surface tensile stress at the floor of arch chamber corresponding to the center of arch width at the edge of hollow slab in the traffic direction is the largest (i.e. the maximum tensile stress \( \sigma_m \)), and the surface vertical displacement of slab corresponding to the center of arch roof at the edge of hollow slab is the largest (i.e. the maximum vertical displacement \( l_v \)). The stress and displacement of the two points are used as the analysis indexes of mechanical responses. Therefore, the relationship curves of \( \sigma_m \) and \( l_v \) with the changes of each geometric parameters of arch chamber are obtained in figure 4 and figure 5.

Figure 4. Change curves of \( \sigma_m \) under each schemes

Figure 5. Change curves of \( l_v \) under each schemes
According to Specifications for Design of Highway Cement Concrete Pavement (JTG D40-2011), the value of allowable tensile stress is chosen as the control index to ensure the sufficient bearing capacity and durability for the concrete hollow slab. The grade of traffic load is set as extremely heavy, and the flexural tensile strength of self-compacting concrete is 5.0 MPa. By the checking formulas of structure ultimate state, the value of allowable fatigue tensile stress of hollow slab structure under the standard axle load can be calculated as 1.65 MPa, and the value of allowable maximum tensile stress is 4.18 MPa under the heaviest axle load (250 kN). Meanwhile, because of the smaller plane size of hollow slab, the temperature stress after checking is very small and negligible.

From Figures 4 and 5, it can be seen that $\sigma_m$ and $l_s$ basically show the significant increasing change trends with the increase of arch width $b$, and 26 cm of Scheme 4 is selected as the appropriate value of $b$ by considering the reasonable force and increasing the size of arch chamber as much as possible. With the increases of floor thickness $l$ and arch height $t$, $\sigma_m$ tends to decrease firstly and then increase slightly, while $l_s$ basically decreases gradually in a very small amplitude, thus 5 cm of Scheme 1 is selected as the appropriate values for $l$ and $t$ separately based on economic considerations. With the increase of roof thickness $h$, $\sigma_m$ and $l_s$ basically show decreasing trends, but when $h$ is less than 6 cm, $\sigma_m$ exceeds the value of allowable fatigue tensile stress and does not meet the bearing capacity requirements, thereby 7 cm of Scheme 5 is selected as the appropriate value for $h$ to prepare easily the model. Therefore, considering the requirements of reliability and economy comprehensively, the suitable sizes of arch chamber for the hollow slab were determined as $b = 26$ cm, $l = 5$ cm, $t = 5$ cm and $h = 7$ cm, respectively, and the corresponding size of hollow slab is $50 \text{ cm} \times 50 \text{ cm} \times 17 \text{ cm}$. After checking, the maximum tensile stresses of the hollow slab under the standard axle load and the heaviest axle load are 1.60 MPa and 3.93 MPa, respectively, and all of them meet the requirements of allowable values. The results show that the structure sizes of hollow slab meet the design requirements.

2.3. Simulation of light path for light-guide body

In order to determine the reasonable structure sizes and materials for the light-guide body, the tracing method of light path was used for the simulation analysis. The solar rays are set to be parallel lines each other with wavelength of 500 nm and irradiance of 1000 W/m$^2$. The distance from the virtual emission surface to the center of light entrance end of convex lens surface is 10 cm, and the refractive index of air is taken as 1. The condensing lens is made of polymethyl methacrylate (PMMA) with refractive index $N$ of 1.49. The light-guide body is a homogeneous body with total reflection around itself which does not absorb solar energy. The light entrance end of convex lens surface and the light exit end of light-guide fiber bottom are total transmission. There is full combination between the interfaces. Therefore, the TracePro software was used for the light path simulation, as shown in figure 6.

![Figure 6. Light path simulation modelling for light-guide body](image)

The design parameters and value-taking schemes for the light-guide body are selected in table 2, where $f$ and $n$ are the surface reflectivity of prism and the refractive index of light-guide fiber, respectively. In order to optimize the structure of light-guide body, the influence laws of various
parameter changes on the light-guide performances of light-guide body were analyzed in accordance with the order of $a \rightarrow r \rightarrow d \rightarrow c \rightarrow n \rightarrow f$, and the appropriate values of each parameters were determined separately. Among them, when a certain parameter change will be analyzed, its values are chosen separately according to each schemes in table 2. The previously determined parameters are chosen according to the determined values, and the subsequently undetermined parameters are taken according to the schemes with "*" in table 2.

| Scheme | Radius $a$ (mm) | Refractive index $n$ | Radius $r$ (mm) | Thickness $d$ (mm) | Height $c$ (mm) | Surface reflectivity $f$ |
|--------|-----------------|---------------------|-----------------|-------------------|-----------------|------------------------|
| 1      | 0.5             | 1.4                 | 1.5             | 0.1               | 0.7$F$         | 0.4                    |
| 2      | 1.0             | 1.5                 | 2.0             | 0.2               | 0.8$F$         | 0.5*                   |
| 3      | 1.5             | 1.6                 | 2.5             | 0.3               | 0.9$F$         | 0.6                    |
| 4      | 2.0             | 1.7*                | 3.0*            | 0.4*              | 1.0$F*$        | 0.7                    |
| 5      | 2.5             | 1.8                 | 3.5             | 0.5*              | 1.1$F$         | 0.8                    |
| 6      | 3.0             | 1.9                 | 4.0             | 0.6               | 1.2$F$         | 0.9                    |
| 7      | 3.5             | 2.0                 | 4.5             | 0.7               | 1.3$F$         | 1.0                    |

The incident angle of sunlight changes periodically every day and every year. The simulation results show that the received luminous flux of light-guide body is less when the incident angle is small, and it is difficult to condense and guide solar rays effectively. Therefore, the solar rays of different incident angles were set at intervals of 10° in the range of 30° ~ 90°, and were irradiated onto the light entrance end of convex lens surface of light-guide body. After condensing and guiding solar rays, the transmitted luminous flux $\Phi_i$ at the light exit end of light-guide fiber bottom can be simulated at the corresponding incident angles. Then the total solar energy $Q$ of single day transmission for the light-guide body can be computed and obtained, and it is used as the evaluation index of light-guide performance. Accordingly, the relationship curves of $Q$ changed with each design parameters of light-guide body can be simulated and obtained in figure 7.

![Figure 7. Change curves of $Q$ under each scheme](image)

From Figure 7, it can be seen that $Q$ increases accelerate with the increase of light-guide fiber radius $a$, and the increase amplitude is most significant, thereby 3.5 mm of Scheme 7 is taken as the appropriate value for $a$. With the increase of convex lens radius $r$, $Q$ increases in a stepped way, and 10.5 mm of Scheme 4 is chosen as the suitable value for $r$ based on economic considerations. With the increase of convex lens thickness $d$, $Q$ increases firstly and then decreases in a single-peak relationship change, and 4.2 mm of Scheme 4 is taken as the suitable value for $d$ by considering the smoothness requirements that the maximum surface clearance of concrete pavement does not exceed 5 mm. The variation laws of $Q$ with the increases of prism height $c$ and refractive index $n$ of light-guide fiber are both increased firstly and then decreased, so that 31.1 mm of Scheme 4 and 1.6 of Scheme 3 are taken as the appropriate values for $c$ and $n$, respectively. The $Q$ value increases gradually with the increase
of prism surface reflectivity $f$. In order to increase the reflectivity, a reflective film can be pasted or coated on the prism surface, and the appropriate value of $f$ is suggested as 1.0 of Scheme 7. Therefore, considering economy and convenient preparation comprehensively, the suitable design parameters of light-guide body structure were determined as $a = 3.5$ mm and $n = 1.6$ for the light-guide fiber, $r = 10.5$ mm and $d = 4.2$ mm for the convex lens, and $c = 31.1$ mm and $f = 1.0$ for the prism, thereby the corresponding total solar energy $Q$ of single day transmission for the light-guide body reaches 5322.2 J.

3. Model preparation and performance test for hollow slab of solar pavement based on light-guide concrete

3.1. Preparation process
Because an arch chamber and multiple light-guide bodies are arranged in the hollow slab of solar pavement of light-guide concrete, it is difficult to vibrate and compact the normal concrete during preparation, and the self-compacting concrete was chosen for casting moulding. According to the above determined suitable materials and sizes for the hollow slab and the light-guide body, the corresponding steel die and light-guide body were manufactured, and the model of hollow slab for solar pavement of light-guide concrete was prepared. The specific process is as follows: assembling steel die → installing and fixing light-guide body → preparing and pouring self-compacting concrete → curing, demoulding and forming hollow slab of light-guide concrete → installing solar panel → installing and connecting solar power generation system. The prepared specimen is shown in figure 8 for the hollow slab of solar pavement of light-guide concrete.

![Figure 8. Specimen preparation of hollow slab for solar pavement based on light-guide concrete](image)

3.2. Mechanical properties testing
The tested compressive strength and flexural tensile strength of 28 day for the self-compacting concrete are 51.3 MPa and 5.5 MPa, respectively, which meet the strength standard of C40. Then the model specimens of concrete hollow slab were prepared and carried on the loading test in material testing system (MTS). Considering the dimension limitation of MTS worktable, the specimen size and the loading head area were reduced by 60% in proportion. According to the contact pressure of 0.7 MPa for the standard axle load, the maximum load was set to 8.7 kN, and the loading rate was 0.6 kN/s, as shown in figure 9. Therefore, the change curve of maximum vertical displacement with pressure was obtained in the center of specimen surface of hollow slab, as shown in figure 10.

Through the simulation of three-dimensional finite element, the maximum vertical displacement and maximum tensile stress in the hollow slab specimen are 7.14 μm and 1.08 MPa, respectively. From Figure 10, it can be seen that the test result of maximum vertical displacement under the standard axle load is 8.55 μm, which is 19.7% larger than the theoretical value. It is mainly caused by the error between the simplified theoretical model and the tested model, but the total deformation is very small. With the increase of pressure, the vertical displacement basically increases in a linear elastic way, and the specimen can fully rebound and recovery to the original state after unloading.
Thus the rationality of simulation results was verified. The results show that the hollow slab of self-compacting concrete has good mechanical properties, and can meet the requirements of safe driving.

Figure 9. Loading test for hollow slab specimen of self-compacting concrete

Figure 10. Change curve of maximum vertical displacement with pressure for specimen

3.3. Power generation efficiencies testing

A solar panel of 12 cm × 12 cm was installed into the arch chamber in the optimized hollow slab to prepare the model specimens of hollow slab for solar pavement of light-guide concrete. The five schemes for the number of light-guide bodies were selected separately, including 25 (Scheme A), 36 (Scheme B), 49 (Scheme C), 64 (Scheme D) and 81 (Scheme E). Through connecting the load of 0 ~ 48 Ω, the open-circuit voltage and the working voltage across load were tested under the direct sunlight of irradiance of 700 W/m². The change curves of output power $P$ with working voltage $U$ were obtained in figure 11, and the analysis results of optimal load and maximum output power were shown in table 3. Where the original solar panel refers to directly placed in the sun for power generation.

Figure 11. Change curves of output power with working voltage for hollow slab specimen

| Scheme   | A  | B  | C  | D  | E  | Original solar panel |
|----------|----|----|----|----|----|----------------------|
| Number of light-guide bodies | 25 | 36 | 49 | 64 | 81 | /                    |
| Optimal load $R$ (Ω)         | 8  | 6  | 5  | 5  | 4  | 5                    |
| Maximum output power $P_{m}$ (W) | 0.714 | 1.092 | 1.415 | 1.705 | 1.769 | 1.636 |

From Figure 11 and Table 3, it can be seen that the optimal load of specimen decreases with the increase of the number of light-guide bodies, while the open-circuit voltage, the output power and the
maximum output power increase, but their increase amplitudes decrease gradually. When the number of light-guide bodies is 64, the maximum output power exceeds the generation power of original solar panel. It shows that the increase of light-guide bodies can improve the power generation efficiencies of solar panel and achieve the effective condensing effects. Therefore, it is suggested that the number of light-guide bodies should be set at 81 and not more than 100. Otherwise, due to the small distance between light-guide bodies, it is difficult for self-compacting concrete to meet the requirements of mouldability during the preparation.

4. Conclusions
According to the dual function requirements of safe driving and clean power generation, a kind of structure model of hollow slab were proposed for solar pavement based on light-guide concrete in this paper. Through mechanical analysis, light path simulation, model preparation and performance testing, it can be concluded that:

1. The maximum tensile stress and the maximum vertical displacement in the pavement structure of rectangular hollow slab with arch chamber cavity increase with the increase of arch width, but decrease with the increase of roof thickness, arch height and floor thickness. The influence of arch width is most significant, but the influences of other three parameters are relatively small. Therefore, based on the requirements of reliability and economy, the suitable structure sizes of hollow slab were determined.

2. The total solar energy of single day transmission of light-guide body increases with the increase of light-guide fiber radius, convex lens radius and prism surface reflectivity, but increases firstly and then decreases with the increase of convex lens thickness, prism height and light-guide fiber refractive index. Among them, the influences of light-guide fiber radius and convex lens radius are relatively significant. Therefore, by considering the condensing and light-guide performances, the suitable geometric sizes and optical parameters of light-guide body were determined.

3. The self-compacting concrete was used to prepare the model specimens of hollow slab for solar pavement of light-guide concrete. The model is high in strength, small in maximum vertical displacement and strong in elastic recovery ability, so that it has good mechanical properties, and can meet the requirements of safe driving. With the increase of the number of light-guide bodies, its working voltage and maximum output power increase continuously, thereby it has higher power generation efficiencies.

In summary, the research in this paper can provide a reference for the research and development of solar pavement, and its application effects need to be verified in the future engineering.

Acknowledgments
This work was supported by National Natural Science Fundation of China (No. 51878077), Transportation standard (quota) program of the Ministry of transport of China (No. 2019-17-077), and Research and innovation program for graduate students in Hunan Province of China (No. CX20190645).

References
[1] Solar Roadways® 2019 Solar Roadways. http://www.solarroadways.com
[2] Northmore AB and Tighe SL 2014 Performance modelling of a solar road panel prototype using finite element analysis Int. J. Pavement Eng. 17(5) 449-457
[3] Northmore AB 2014 Canadian solar road panel design: a structural and environmental analysis MD Thesis of the University of Waterloo
[4] SolaRoad® 2019 SolaRoad. http://www.solaroad.nl
[5] COLAS® 2019 Wattway. http://www.wattwaybycolas.com/en
[6] Dezfooli AS, Nejad FM, Zakeri H and Kazemifard S 2017 Solar pavement: a new emerging technology Sol. Energy. 149 272-284
The first expressway photovoltaic pavement test section in the world is officially opened to traffic. http://www.qljfjt.com/detail_3835.html

Zeng J 2013 Mechanical analysis of hollow slab pavement structure MD Thesis of Changsha University of Science & Technology

Zha XD, Zhang CJ, Wu ZJ and Zhang QS 2016 Mechanical analysis and model preparation for hollow slab element of solar pavement Acta Energiae Solaris Sinica. 37(1) 136-141

Zhang CJ 2017 Research on preparation and performance of hollow slab model of solar pavement based on light guide concrete MD Thesis of Changsha University of Science & Technology