

Cellular Porous Brick—A Novel Permeable Pavement Strategy

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Abstract

Permeable pavement is generally considered as one of the most effective practices of rainwater management. This paper analyses the defects of current permeable pavement. Inspired by the honeycomb bionic structure which has superior mechanical properties and structural efficiency, an innovative “honeycomb-like” model of permeable brick measuring $190 \times 100 \times 60$ mm in size was proposed and constructed. The mechanical strength and permeability performance of the honeycomb permeable brick were experimentally assessed by universal testing machine and artificial rainfall equipment, respectively. Experiment results demonstrated an excellent performance in compressive tolerance and permeability. The critical damage load (F_c) and compressive strength (E_c) of honeycomb brick were 336.46 KN and 17.70 MPa, which were 18.06% and 11.04% higher than that of ordinary solid permeable bricks, respectively, compared with the conventional permeable bricks. The honeycomb brick is capable of increasing the permeability coefficient by 19.2% and 11.96% under rainfall repetition period of 20 and 30 years respectively. These results demonstrated that the permeable brick with honeycomb-like structure can provide a new paving strategy for the construction of sponge city.

Keywords

Permeable Pavement, Honeycomb Structure, Mechanical Properties, Permeability

1. Introduction

Rapid urban expansion in many cities has resulted in that vegetation cover was replaced with impervious surfaces for the construction of buildings and associated infrastructure [1] [2] [3]. The diminishing of permeable coverage in urban

area, especially in rain-rich region such as south china, may frequently cause vast runoff of storm-water in summer [4].

Urban water-related issues have raised concerns worldwide among scientific communities, and water management is an essential aspect in the sustainable development of urban areas [5] [6]. A larger number of solutions have been suggested to address water problems for urban areas including the best management practices (BMPs) in the United States [7], sustainable urban drainage systems (SUDS) in the United Kingdom [8], the low impact development (LID) strategy in New Zealand as well [9], water sensitive city (WSC) or water sensitive urban design (WSUD) in Australia [10]. All of these novel concepts and strategies were aimed at preserving and maintaining the natural drainage runoff profile as much as possible [11] [12].

For developing countries like China, most urban areas have witnessed high population growth, intensive expansion of impermeable roads and rooftops [13]. In order to alleviate urban water-related problems, the urban water management strategy name as “sponge city” has been implemented as an adaptation measure to address urban water issues in China since 2013 [14]. It emerges that Sponge City has four main principles; these are: urban water resourcing, ecological water management, green infrastructures, and urban permeable pavement [15]. Among the above Sponge City strategies, many studies have found that the performance of permeable pavements in terms of flooding reduction was even better and more effective than other Sponge City technologies, including green roofs or rainwater resourcing [16] [17].

There are four main types of infiltration pavements: permeable concretes, permeable asphalts, grass pavement, and permeable interlocking concrete pavers available in current market [18]. However, these permeable pavements, have common disadvantage that cannot achieve the combination of pervious and structural strength. The permeability of permeable pavement, is greatly affected by the porosity, which also has an significant inverse relationship with the structural strength. Therefore, how to improve the capacity of permeability under the premise of not reducing the bearing capacity and structural strength of the road and square has become one of the technical barriers in urban sponge transformation.

Extensive great inventions originated from the imitation of nature in human history. Due to its superior mechanical properties and structural efficiency, honeycomb structure has been widely used in chemical industry, aerospace, national defense and other fields [19]. However, despite that honeycomb structure has excellent mechanical properties and permeability, research has mainly focused on permeable concrete, permeable asphalt, or open-graded asphalt concrete mixture, etc. In the design of permeable pavement or in the construction of sponge city, there are to date no studies concerning the attempts and practices of applying the honeycomb structure in permeable pavement, and there is no concept of “honeycomb-like” sandwich structure proposed in domestic and abroad.

Therefore, the objective of this study is to assess the potential application foreground of honeycomb structures in the sponge transformation of urban hardened ground such as roads, squares, parking lots, and urban site walkways. A novel honeycomb-like permeable brick was designed and mechanical properties of which were tested by laboratory experiment. The performance in term of bearing capacity, permeability, cost and manufacturing process between honeycomb bricks and conventional permeable concrete bricks were also compared in this study.

2. Materials and Methods

This section presents the raw materials used in this experiment, the manufacturing process of honeycomb permeable brick, as well as the test and analysis methods used in this project.

2.1. Raw Material

Cement (P.C32.5R) was purchased from Sichuan Xing Chuan Cheng Cement Co., Ltd. Concrete early strength agent (DC-C13) was supplied by Beijing Dechang Weiye Construction Engineering Technology Co., Ltd. Coarse aggregate (3 - 5 mm) and Fine aggregate (bulk river sand) were obtained from Baiyun District, Guangzhou. HJW-30 forced single horizontal shaft concrete mixer was provided by Shanghai Juhong Instrument Equipment Co., Ltd. Resin model was provided by Wuhan Ruyi plexiglass products factory. Honeycomb socket model was designed and manufactured by Shenzhen Jingrui 3D Printing Technology Co., Ltd.

2.2. Sample Manufacture

The manufacturing process of honeycomb permeable brick is shown in **Figure 1**. Concrete was prepared with a proportion of coarse aggregate: fine aggregate: cement: water 20:12:5:3, then poured the mixture into the resin model with hexagon prism and compacted manually after fully mixed. After that, the model was sealed and demoulded after 24 hours, and then placed in a ventilated circumstance for natural drying and waiting for testing.

The materials, models and finished products were shown in **Figures 2(a)-(c)**, respectively. The dimension of honeycomb permeable brick was $190 \times 100 \times 60$ mm with honeycomb hole of 9 mm in diameter. The bricks without honeycomb hole were used as the reference and named W-1. Two kinds of bricks made of the same materials.

2.3. Test Methods and Equipments

After drying, the main physical parameters such as cell size, density, porosity,

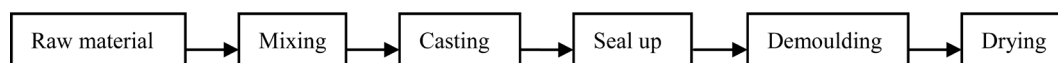


Figure 1. Manufacturing process of honeycomb permeable brick.

and major mechanical properties as plane compressive strength, shear strength, as well as permeability of the samples were tested during experiment.

2.3.1. Physical Parameters

The main physical parameters of honeycomb permeable brick were tested as follows: Density test was determined using the electronic balance (KF-H2 type, Zhejiang Jinhua Kaifeng Group Co., Ltd.) according to ASTM C271 standard [20]. The cell size was measured by vernier caliper according to BMS8-124AB standard.

2.3.2. Mechanical Properties Test

The compressive strength and shear strength of honeycomb were tested by electronic universal testing machine (WAKE type electro-hydraulic servo universal testing machine, Guangcai Testing Instrument Co., Ltd.) (Figure 3). The major tested parameters include the maximum bearing capacity (FBC/KN), yield load (FSC/KN), maximum compressive strength (σ_{BC} /MPA), yield limit (σ_{SC} /MPA) and compressive strength (EC/GPA) of honeycomb along the thickness direction, etc. All aforementioned parameters were tested according to ASTM C365 [21], and ASTM C273 [21] [22].

2.3.3. Permeability Test

For permeability coefficient (mm/s) tests the method outlined in Zhao Fei *et al.* [23] was adopted. As shown in Figure 4, the artificial rainfall simulation system consists of an artificial rainfall equipment, a test tank, water collection equipment,

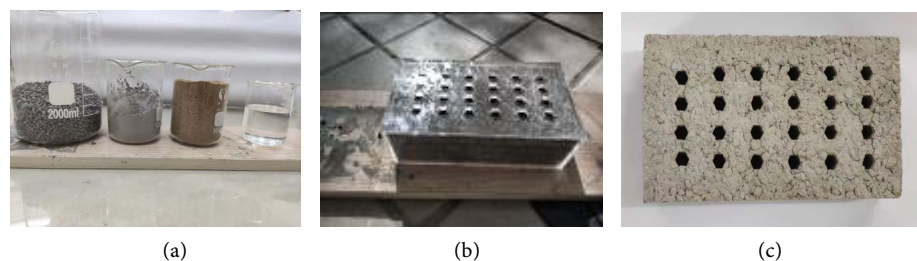


Figure 2. Materials (a), mould (b) and finished products (c).

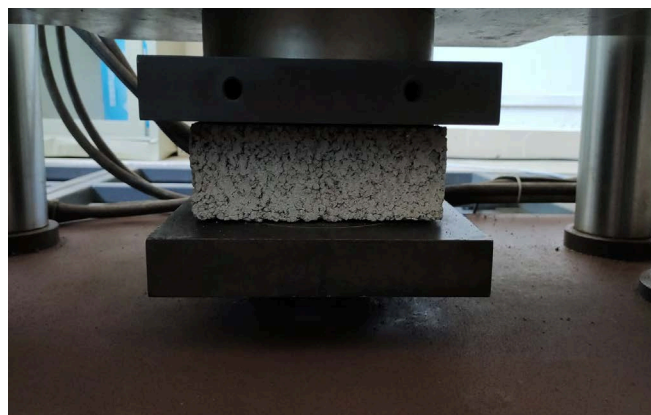


Figure 3. Compression test of electronic universal tester.

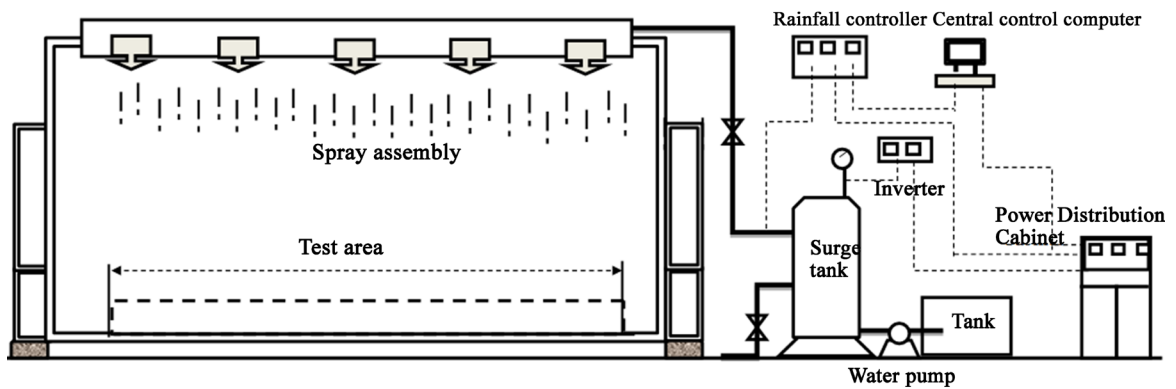


Figure 4. Rainfall model and permeation test.

and control equipment. The principle of superimposed spraying rainfall was adopted, *i.e.* multiple groups of rainfall sprinklers are arranged in the rainfall coverage area. When each group of sprinklers works alone, it can cause a stable rainfall intensity in the coverage area, while the combination of each group sprinklers can cause different rainfall intensity. The brick samples were placed in the test tank. The rainfall, seepage and rain time were recorded during experiment.

The Permeability coefficient of the Honeycomb brick was tested according to Darcy's law, which was calculated using the following formula:

$$\Psi_{N,t_c} = \frac{P_{N,t_c} - W - K_j \cdot t_c}{P_{N,t_c}} \quad (1)$$

where Ψ_{N,t_c} is the runoff coefficient under repetition period of n years and rainfall duration of T_C ; T_C is the rainfall duration (min); P_{N,t_c} is the rainfall under N years repetition period and T_C (mm) rainfall duration; W is the water capacity of permeable brick (mm); K_j is the saturated conductivity of soil base (mm/min).

3. Results and Analysis

The follow sections presented the representative results obtained in current experiment.

3.1. Physical Parameters of Honeycomb Permeable Brick

The densities of bricks are inversely related to the porosity, which is also linked to their potential of permeability. As shown in **Table 1**, the density of sample Y-1 was 2037.37 kg/m³, 3.49% lower than that of W-1 (2108.42 kg/m³). The porosity of Y-1 was 22.57%, 9.34% higher than that of W-1 (13.23%). These observations imply a considerable permeability differences between two samples.

3.2. Mechanical Properties of Honeycomb Permeable Brick

Table 2 presents the results of strength tests of two permeable brick samples. It clearly shows that the compressive strength and failure load of W-1 were significantly lower than that of honeycomb brick Y-1. Because the two samples have

identical sizes, material and process methods, the hexagon honeycomb hole could be the main factor that contributed to the difference of compressive strength and failure load between W-1 and Y-1. As shown in **Table 2**, the compressive strength of honeycomb permeable brick (Y-1) was 24.21% higher than that of W-1, which indicated that the bearing capacity of porous brick increased instead of decline with reduced material consumption. Analogously, the failure load of W-1 was 285 KN, which was 15.29% lower than that of Y-1. These results demonstrated that the honeycomb structure has excellent mechanical properties of compression resistance and energy absorption.

It can be seen from **Figure 5** that each mechanical index of honeycomb brick is superior to that of solid bricks, e.g. the failure load and cracking load of sample Y-1 are 18.06% and 11.04% higher than W-1 respectively. These results suggest a potential linkage between the honeycomb structure and its mechanical properties. As reported in the previous researches, pore structure was able to prevent stress concentration occurred in the plate with arc-shaped hole lattice [19], which was also in accordance with the phenomenon that the arch structure presented more superior compressive strength. Furthermore, as plotted in **Figure 5**, the failure load (Fbc) of Y-1 was approximately 6.32% higher than its cracking load (Fsc), while the failure load of sample W-1 was equal to the cracking

Table 1. Physical parameters of honeycomb permeable brick.

| Sample No. | Honeycomb hole size/mm | Density (kg·m ³) | Porosity (%) |
|------------|------------------------|------------------------------|--------------|
| Y-1 | 8.90 | 2037.37 | 22.57 |
| W-1 | - | 2108.42 | 13.23 |

Table 2. Data sheet of compression experiments.

| Sample number | Length (mm) | Width (mm) | Compression area (cm ²) | Compressive strength (Rc/MPa) | Failure load (P/KN) |
|---------------|-------------|------------|-------------------------------------|-------------------------------|---------------------|
| Y-1 | 190 | 100 | 19,000 | 17.70 | 336.461 |
| W-1 | 200 | 100 | 20,000 | 14.25 | 285.010 |

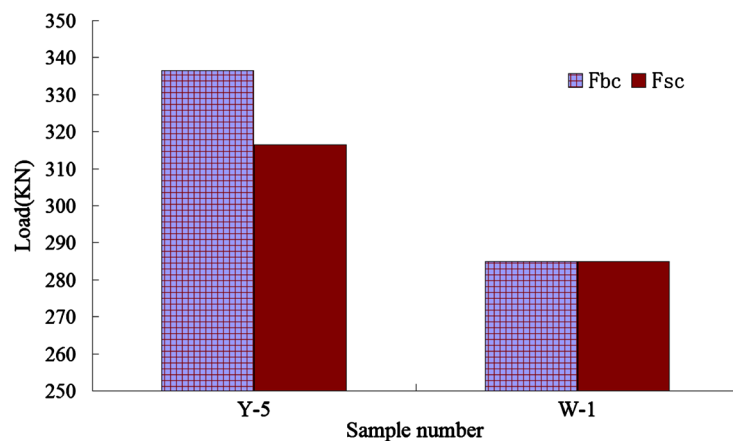


Figure 5. Maximum load (Fbc/KN), yield load (Fsc/KN) of each sample.

load according to the test results shown in **Figure 5**. This behaviour can be imputable to the excellent elastic deformation resistance of the honeycomb structure, for which it would not possibly resulting in a collapse to the test block immediately even if the external force exceed the yield limit of honeycomb brick. As documented in previous studies, the deformation of honeycomb structure can be categorized into four stages, they are: elasticity, elastoplasticity, plasticity and compaction [24]. It is hypothesized that even if the honeycomb brick has cracked during the process of compressing, the wall of honeycomb hole may forms a strengthened column, which could effectively prevent the cracks to develop along a specific path [25], thus to delay a structural collapse take place in the brick.

Figure 6 presented the stress deformation curve of honeycomb brick Y-1 and solid brick W-1, respectively. **Figure 6(a)** shows that the maximum deformation of sample Y-1 was less than 15 mm when subjected pressure increased from 0 to 145 KN. By contrast, the maximum deformation of sample W-1 was higher than 22.5 mm under pressure ranged from 0 to 90 KN (seen **Figure 6(b)**). It was obviously that, as compared to solid brick, smaller deformation occurred in the honeycomb brick when bearing identical pressure.

It can be seen from **Figure 6**, the sample of Y-1 presented a continuous and stable deformation curve under stress during the whole test period. In contrast, W-1 undergoes two severe deformations under load of 18 KN and 82 KN respectively. These behaviours were mainly attributed to the unique porous structure of honeycomb brick. On the one hand, the honeycomb unit was able to effectively buffer the radial external force (lateral force), thus lead to a smaller

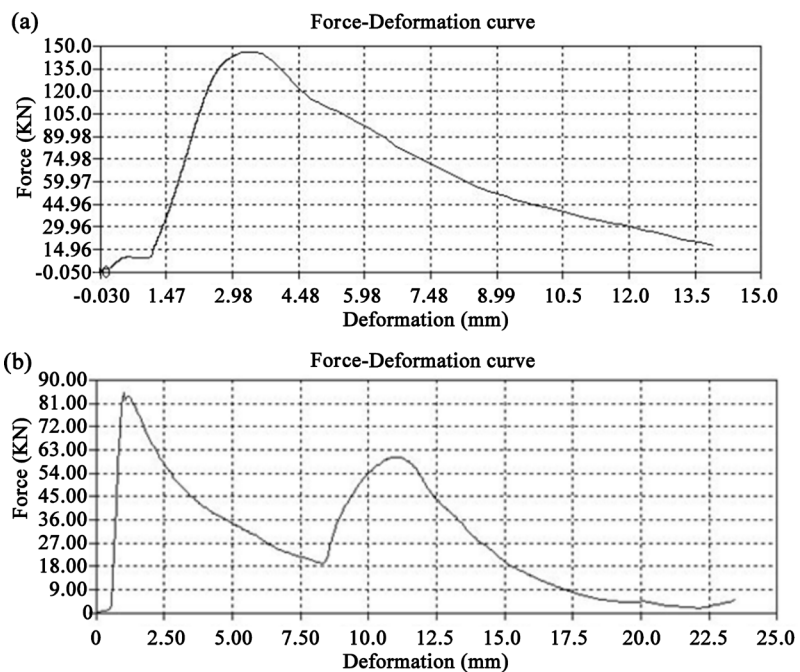


Figure 6. Stress-deformation curves of honeycomb bricks (a) and conventional bricks (b). (a) Y-1; (b) W-1.

stress and deformation. On the other hand, as the honeycomb unit can act as a spring to buffer the radial force (lateral force), thereby allowing most of the deformation and stress concentrated in several honeycomb cells adjacent to the bearing point of external force, thus leading to a reduced stress and deformation for other parts of the bricks [26].

3.3. Permeability

Figure 7 shows the permeability of two samples. Permeability coefficient is often used as a technical index to evaluate the infiltration performance of permeable pavement [27]. As can be seen from Figure 7, the permeability coefficient of honeycomb brick (Y-1) was 5.72 mm/s under P20 (a designed rainfall repetition period of 20 years), and was 6.74 mm/s under P30, which was 19.2% and 11.96% higher than that of solid-brick (4.80 mm/s and 6.02 mm/s under P20 and P30, respectively). The design of porous structure in the honeycomb brick, leading to a higher porosity of the pavement, as a consequence, contributes to the improvement of permeability.

3.4. Comparison with Traditional Permeable Brick

As can be seen from Table 3, the porous honeycomb has significant advantages in terms of compressive strength, shear resistance, porosity and permeability in comparison to several conventional permeable pavements. The excellent performance of honeycomb brick in compressive strength and flexural (shear) strength, were mainly due to its porous structure, which could more effectively diffuse pressure stress and anti-deformation [26]. As a result of the internal porous structure, leading to a higher porosity of the brick, would also contribute to the enhancement of permeability.

In addition, honeycomb brick has significant advantages in cost, which is linked to its porosity structures that substantially reduced consumption of material. As reported in Table 3, the manufacturing processes of the honeycomb brick are uncomplicated in comparison to permeable concrete, permeable asphalt, and sintered brick.

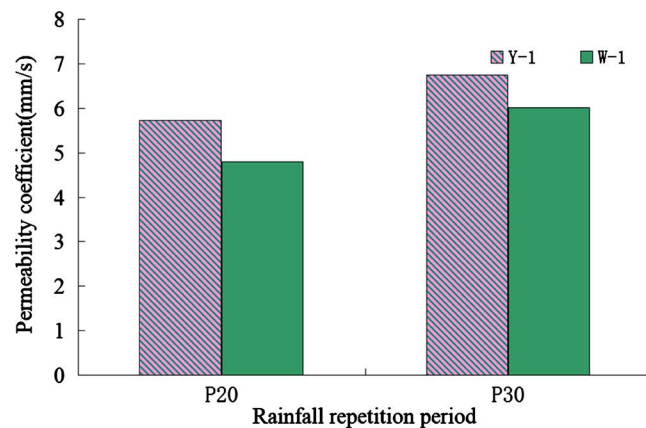


Figure 7. Permeability coefficients of two samples.

Table 3. Comparison of raw materials, manufacturing methods, technical indexes and application scope of several kinds of permeable bricks.

| Classification | | Permeable concrete | Porous Asphalt | Sintered permeable brick | Porous honeycomb brick |
|------------------------|-------------------------------|--|---|---------------------------------|---|
| Raw material | | Cement, continuous graded aggregate | Single graded aggregate, asphalt | Inorganic nonmetallic materials | Continuous graded aggregate, cement |
| Manufacturing methods | | Mixing—stirring—compaction | Mixing—stirring—compaction | Shaping—Fired | Mixing—stirring—compaction |
| Performance | Compressive strength/MPa | 15 - 30 | 15 - 30 | 25 - 35 | 15.15 - 23.22 |
| | Flexural Strength/MPa | 3.0 - 5.0 | 3.0 - 5.0 | 4.5 - 6.0 | 8 - 11 |
| | Porosity % | 10 - 25 | 10 - 25 | 15 - 20 | 16.2 - 22.6 |
| | Permeability coefficient/mm/s | 1.0 - 10.0 | 1.0 - 10.0 | 1.0 - 15.0 | 5.72 - 9.26 |
| Cost and applicability | | High temperature and humidity resistance, low strength | High strength, low temperature and humidity resistant | High abrasion resistant | High strength, high permeability coefficient and low cost |

Data cited from references [1] and [2].

4. Conclusion

In this study, an innovative “honeycomb-like” permeable brick was proposed and the mechanical strength and permeability performance of this novel honeycomb permeable brick were assessed. The experiment results confirmed that the honeycomb porous permeable brick has superior compressive strength and permeability in comparison to the conventional permeable pavements. The compressive strength and failure load of honeycomb brick were 24.2% and 18.1% higher than that of solid brick respectively, and the permeability was 19.2% - 53.8% higher than that of solid-brick. This study provided new methods for the sponge transformation of urban hardened ground, such as city square and pedestrian street.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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