Structural Design of Prefabricated Sidewalk in Sponge City

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Abstract. In the traditional pavement design, rainwater is mainly discharged by surface runoff, and in the structural design, the key point is the pavement waterproof. Therefore, the traditional sidewalk design is inconsistent with the requirements of sponge city. The research basis of this paper comes from a field engineering, the structural parameters of prefabricated sidewalk and the corresponding design methods are studied and summarized. The structural function of sidewalk is realized by superposition and combination of each structural layer. For the realization of prefabricated sponge sidewalk technology, the function of each structural layer must be fully considered, and the function of each structural layer should be designed and combined according to the design purpose. The results show that, by discussing the function of each layer of prefabricated sidewalk, the structural layer of prefabricated sidewalk is preliminarily determined (see Figure 2 in main text); according to the strength requirements and water permeability requirements of the structure, the thickness range of the structural layer is 13.11cm-21.3cm; finally, the relationship between plate thickness and critical position load, temperature fatigue stress, and finally determines the thickness of precast cement concrete slab is 15cm.

1. Introduction

Sidewalks are an important part of urban infrastructure and urban environmental carriers, and the construction and maintenance of sidewalks not only meet the traffic requirements of municipal roads, but also reflect the modernization and civilization level of a city [1,2]. With the implementation of the sponge city concept one by one, sidewalks, as an important part of slow traffic, have received widespread attention [3-5]. In order to improve the quality of the construction, the water permeability and speed up the paving speed, a comprehensive upgrade of the original pavement structure of the sidewalk is to meet the urgent need. Factory-based prefabricated assembly technology can make the sidewalk surface layer have good durability, flatness and sponge characteristics [6,7]; the corresponding base layer is changed from the original cast-in-place concrete to a permeable and non-cast-in-place base layer to keep the construction fast and Less cast-in-place guarantees the advantages of environmental friendliness while minimizing traffic interference. As the prefabricated technology has been popularized and applied in construction, bridges, tunnels and other projects [8-10], this research and development technology is the first research and application of prefabricated technology in urban slow traffic, which expands the application range of superior technologies. Due to structural changes, the structural design of the sponge prefabricated sidewalk is inconsistent with the structure of
conventional paving tiles. Therefore, the research in this paper is to study the structural parameters of the prefabricated sidewalks required by sponge.

2. Comparative Analysis of the Two Structures

2.1. Existing Structure

Most of the current sidewalks are composed of “soil foundation + concrete foundation + sand leveling layer + block brick paving layer” [11,12]. Conventional sections have adopted this structure, and the specific structure is shown in Figure 1.

![Figure 1](image.png)

**Figure 1.** Representative drawing of existing sidewalk structure drawing.

According to Figure 1, the base layer of the existing structure adopts C20 concrete base layer. This kind of structure layer needs to reserve a large area on site, add cement concrete mixing or storage equipment and pour it, and it will take a long time to cure. The surrounding environment will have an impact and the construction period will be longer.

2.2. Innovative Structure Design

Analysis of the structure and function of the sidewalk, different structures have different materials to choose from, which will produce many structural combinations. The structural combination is not a simple arrangement and combination but gives full play to the characteristics of the materials used. And each material should be compatible [13], the structure layer should be coordinated, and the final design combination should be economical and practical [14].

1) Surface layer: For the surface layer, it should be ensured that the layer has sufficient mechanical strength [15], and it needs to be suitable for prefabricated construction. Therefore, a composite structure of reinforced cement concrete frame + permeable cement concrete is designed;

2) In view of the further increase in the thickness of the prefabricated sidewalk as the surface layer and the improvement of the structural strength, the strength of the base layer can be appropriately reduced. Therefore, the convenient technology replacement of the base layer is a problem that can be solved in the design of the fabricated sidewalk structure layer.

3) Base course and cushion: For drainage sidewalks, the base course and cushion should not only bear the load transmitted from the surface layer, but also take into account the functions of water permeability and water storage. Considering that the surface layer already has higher mechanical properties, the original. The concrete is poured into the base, and a gravel base is designed to have the function of a cushion. At the same time, a permeable pipe is set in the gravel base to collect rainwater and drain. The designed structure is shown in Figure 2.
3. Parameters of the Prefabricated Permeable Cement Concrete Structure Scheme

3.1. Rainfall Intensity

The prefabricated sponge sidewalk belongs to the category of permeable sidewalks, and its structural design should be combined with local hydrological conditions. According to the current design requirements for permeable sidewalks, the first consideration is rainfall conditions [16]. Therefore, local weather data should be collected and sorted out during design. The main content includes parameters such as rainfall intensity and return period. This paper takes Shanghai as an example, combined with local precipitation data, to determine the relevant parameters of permeable sidewalks.

Shanghai is located between 120°52′ to 122°12′ east longitude and 30°40′ to 31°53′ north latitude. The land area is 6340.5 square kilometers. It is located on the west coast of the Pacific Ocean, the east coast of the Asian continent, and the center of the north and south coasts of China. Shanghai has a subtropical monsoon climate with four distinct seasons, abundant sunshine and abundant rainfall. The climate in Shanghai is mild and humid, with short spring and autumn and long winter and summer. In 2013, the city's average temperature was 17.6°C, sunshine was 1885.9 hours, and precipitation was 1173.4 mm. More than 60% of the annual rainfall is concentrated in the flood season from May to September [17]. This paper uses the rainstorm intensity formula in the Shanghai local standard "Heavy Rain Intensity Formula and Design Rain Pattern Standard" for calculation. The calculation formula is shown in Formula 1.

\[ q = \frac{1600 \cdot \left(1 + 0.846gp\right)}{\left(t + 7.5\right)} \]  

Where:
- \( q \) —— Design rainfall intensity, L/(s·hm²);
- \( p \) —— design return period, years;
- \( t \) —— rainfall duration, min.

According to Formula 1, we can determine the rainfall intensity through the rainfall return period and rainfall duration. As refer to the guidelines [12,18] that "the water storage capacity of permeable surface facilities should not be lower than the rainfall with a return period of two years". Therefore, the return period \( P=2 \) is chosen, and set the condition that “one hour of rainfall will not cause surface runoff on the sidewalk”. Incorporating these data into Formula 1, the design rainfall intensity \( q=54.9\text{mm/h} \). The reason why the rainfall time is 1h is: because this article only considers the impact of short-term heavy rainfall on drainage sidewalks, because slow traffic only controls surface runoff, short-term heavy rainfall is the main cause of runoff, and the duration of heavy rainfall is usually Not too long.

3.2. Thickness Range of Structural Layer Based on Water Permeability Requirements

In common permeable sidewalks, the base layer is often used as a temporary water storage structure, and rainwater seeps through the soil foundation in the base layer and is finally drained away. The
water storage structure of the base layer can be divided into saturated and unsaturated layers at any time, which is a dynamic division of the base structure. The mechanical properties of the pavement can be ensured by measuring the thickness of the base layer. At the same time, the calculation of water storage thickness is also a reference index for the design of structural layer thickness. The drainage sidewalk can regard the side water outlet as the bottom water outlet of the permeable sidewalk, so as to derive the thickness calculation formula with reference to the permeable sidewalk [19]. Set rainwater infiltration strength $W_t$, cm/s and rainwater infiltration strength $V_t$, cm/s, Figure 3 is a simplified schematic diagram of the structure.

![Figure 3. Expansion rate of foamed asphalt.](image)

According to the water balance theory:

\[ A k(h(t)) = A \int_0^t (W_t - V_t)dt \]  
\[ h(t) = \frac{1}{k} \int_0^t (W_t - V_t)dt \]

Where:
- $k$ = effective void ratio of the base layer;
- $t$ = precipitation duration;
- $h(t)$ = storage height at time $t$.

Simplify the above integration and take the average rainfall intensity $i$ as the rainfall intensity. Because there is no runoff on the road surface, it means that the infiltration intensity is greater than the rainfall intensity. Take $w(t)=i$, and the infiltration intensity is taken as the intensity of rainwater discharged into the soil foundation. It can be regarded as the average velocity $V$, and we get:

\[ H = \left(0.1i - 3600q\right)t/(60v) \]

Where:
- $H$ — Thickness of permeable sidewalk structure, cm;
- $i$ — Intensity of regional rainfall, mm/h;
- $q$ — The average permeability coefficient of soil foundation;
- $t$ — The duration of rainfall, min;
- $v$ — The average air void ratio of permeable sidewalk structure layer.

The permeable sidewalk materials will be studied later, and the calculations will be performed after determining the value of each parameter. The designed air void ratio of the permeable surface layer is about 25%, the air void ratio of the base layer is between 35%-40%, and the average permeability coefficient of the soil foundation is $1*10^{-4}$cm/s, which can be obtained after substituting the above formula. The thickness range is 13.11cm-21.3cm.

3.3. Accurate Calculation of Plate Thickness Design

The thickness of the cement concrete slab relates to the carrying capacity of the precast slab. To calculate the structural strength, the following assumptions are made:

(1) Since the applied situation are the urban roads, the calculation is carried out according to the medium traffic load level, and the structural reliability is 1.2;
(2) According to the sidewalk surface structure, it is slab surface + gravel base (10cm) + soil foundation (modulus ≥ 20MPa). The temperature warping stress of the concrete road slab at the maximum temperature gradient is calculated according to Formula 6,

$$\sigma_i = \frac{E \alpha_i \Delta T}{2(1 - \mu_c)}$$  \hspace{1cm} (5)

Where:

- $\sigma_i$ — Concrete temperature expansion coefficient
- $\alpha_i$ = $1 \times 10^{-5}/°C$
- $\Delta T$ — Temperature difference between concrete pavement slab and lower layer, $\Delta T = T_g \times h$, $h$ is the thickness of the road slab, the recommended value and correction coefficient of the maximum temperature gradient value $T_g$ are shown in Table 1;
- $\mu_c$ — Poisson’s ratio of concrete, $\mu_c = 0.15$

**Table 1.** The maximum temperature gradient of each highway’s natural zoning.

| Natural division | II, V | III | IV, VI | VIII |
|------------------|-------|-----|--------|------|
| Maximum temperature gradient (°C /cm) | 0.83-0.88 | 0.90-0.95 | 0.86-0.92 | 0.93-0.98 |

For the pavement of concrete slabs for sidewalks, the fatigue stress of the critical position of the pavement structure under different precast slab thicknesses need to be calculated, in the state of the action of driving load and temperature load (which are multiplied by the corresponding reliability) [20]. The relationship between panel thickness and critical position load+temperature fatigue stress result is shown in Figure 4.

**Figure 4.** The relationship between plate thickness and critical position load and temperature fatigue stress.

When the thickness of the precast slab is greater than 15cm, the fatigue load stress under the critical position load and temperature of the precast slab is less than 4MPa of the flexural tensile strength of the permeable concrete. When the thickness of the precast slab is greater than 15cm, the fatigue load stress under the critical position load and temperature of the precast slab is less than 4MPa of the flexural tensile strength of the permeable concrete. Therefore, considering factors such as cost and weight, the thickness of the precast cement concrete slab is selected as 15cm.

**4. Conclusions**

1) By discussing the role of each layer of the prefabricated sidewalk, the structure layer combination of the prefabricated sidewalk is initially determined, see Figure 2.
2) According to the rainfall intensity in Shanghai, the calculation method for the thickness of the structure layer of the sidewalk was determined, and the thickness of the structure layer was finally determined to be between 13.11cm-21.3cm.
3) According to the strength requirements of the structure and the requirements of water permeability, the thickness of the precast cement concrete slab is finally determined to be 15cm.
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References
[1] Wei Baoban. The humanized space of urban roads. South China University of Technology, 2013.
[2] Yachtani Yoshitaka, Matsuzaki Kazuhiro, Ito Akahiko, etc. Application of high strength rc precast slab pavements in airports. Papers on Paving Engineering, 2003, 8: 183-193.
[3] Du Zhonghua. Application of Sponge City Concept in Urban Road Engineering. Construction & Design for Engineering,2016(03):69-71+73.
[4] Erhan Güneyisi, Mehmet Gesoğlu, Kareem Q , et al. Effect of different substitution of natural aggregate by recycled aggregate on performance characteristics of pervious concrete. Materials and Structures, 2014, 49(1-2):521-536.
[5] Chandrappa A K , Biligiri K P . Pervious concrete as a sustainable pavement material – Research findings and future prospects: A state-of-the-art review. Construction and Building Materials, 2016, 111:262-274.
[6] Zhou Zemin. Construction of prefabricated cement concrete pavement. Central South Highway Engineering, 1991(3):20-23.
[7] Zhang Yi. Research on prefabricated high-strength permeable concrete pavement. Changsha University of Science and Technology. 2017.
[8] Liu Yongjian, Gao Yumin, Zhou Xuhong, Zhang Zejun, Zhang Yuanfang. Technical and economic analysis of small and medium span steel-concrete-composite girder bridges. China Journal of Highway and Transport,2017,30(03):1-13.
[9] Yao Yiwen, Jiang Lihua, Fan Yiqun. Overview of prefabricated assembly technology of underground space structure. Urban Roads Bridges & Flood Control,2012(09):286-292+344.
[10] Wang Jun, Zhao Jida, Hu Zongyu. Development status and thinking of my country's construction industrialization. China Civil Engineering Journal,2016,49(05):1-8.
[11] Ma Hailong. Analysis on the construction of road prefabricated sidewalks. Science and Technology Innovation and Application, 2013(15):223.
[12] DGTJ08-2241-2017. Technical specification for permeable sidewalk. Shanghai: Press of Tongji University
[13] Ito Akahiko, Yamawaki Hiroshi, Tanaka Hideki, etc. Basic examination about the design of the high strength rc precast pavement slab in airport. Collection of Pavement Engineering,2003, 8: 173-181.
[14] Novak J, Kohoutková A, Krístek V, et al. Precast concrete pavement – systems and performance review[J]. 2017, 236(1):012030.
[15] Wang Xiangying, Chen Pengfei, Yang Chao, et al. Analysis of factors affecting the performance of prefabricated road slabs. Low Temperature Construction Technology, 2019(5).
[16] Liu Wen,Feng Qi,Deo Ravinesh C,Yao Lei,Wei Wei. Experimental Study on the Rainfall-Runoff Responses of Typical Urban Surfaces and Two Green Infrastructures Using Scale-Based Models. Environmental management,2020.
[17] http://www.china.com.cn/aboutchina/zhuanti/09dfgl/2009-09/08/content_18488374.htm
[18] GB 50400-2016. Technical code for rainwater management and utilization of building and sub-district. Beijing: China Construction Engineering Press
[19] Wu Shitao. Structure and structure of prefabricated cement concrete pavement. Tongji University, 2017.
[20] Huang Ming, Wen Xuejun, Lu Hewei. Analysis on Mechanical Performance of Precast Assembled Pervious Concrete Sidewalk Slab. Urban Roads Bridge & Flood Control, 2019(5):237-240