Design and performance of urban sponges in red soil: improvement of physical and chemical properties

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ABSTRACT

This study investigated the physical and chemical properties of a single or combination of permeable materials which can be used as fillers in the Sponge City program in China. Four types of fillers, perlite, coral sand, vermiculite and ceramsite, were selected from six alternative fillers by an analytic hierarchy process. The optimal city sponge, which consists of vermiculite (10 cm), ceramsite (15 cm), perlite (15 cm), coral sand (20 cm) and Canna indica L, was found by the orthogonal experiment (L16(45)). The results of the simulated rainwater experiment of the optimal sponge showed that the permeability coefficient K10, NH3-N, total phosphorus (TP) and chemical oxygen demand (COD) removal rate were 1.20 ± 0.23 mm/s, 96.6 ± 0.2%, 36.8 ± 0.07% and 9.6 ± 0.07% respectively. The results suggested that the optimal sponge had an excellent treatment effect on NH3-N in rainwater while ensuring rapid infiltration. It provided a simple, economical and effective method for rainwater treatment and the Sponge City program in the future.

Key words | analytic hierarchy process, rain garden, rainwater runoff, red soil, sponge city

INTRODUCTION

In recent decades in China, about ten million people have entered cities (Qiu 2015) every year. As a result of urbanization, a large number of buildings were built, resulting in decreased green areas and an increase of impervious zones, which increased the risks of urban flooding. In China, the economic loss and casualties in cities affected by flooding have increased significantly (Liao et al. 2016). In 2011, the worst urban waterlogging occurred in China, which caused nearly 400 billion yuan of economic losses (Wu et al. 2016). In 2016, 28 provinces in China experienced severe flooding during weeks of torrential rainfall (Jiang et al. 2018). Urban rainwater management has become a serious challenge.

Meanwhile, many strategies promoting integrated management of urban water have been practiced among industrialized nations. Such efforts include the Low-Impact Development (LID) in the United States (Pyke et al. 2011), the British Sustainable Urban Drainage System (SUDS) (Mitchell 2005) and the Australia Water-Sensitive Urban Design (WSUD) (Morison & Brown 2011), as well as the LID in New Zealand, and the Low-Impact Urban Design and Active, Beautiful, Clean-water Program (ABC) in Singapore, to name just a few (Voyde et al. 2010). After studying these practices, the concept of ‘sponge city’ was formally introduced by the Chinese government in December 2013 (Wang et al. 2013). Since then, the concept of sponge cities has been actively promoted by the Ministry of Housing and Urban-Rural Construction and the Ministry of Water Resources have actively promoted sponge cities. The purposes of ‘the Sponge City’ are as follows: (1) Improving effective control of urban peak runoff, and improving the abilities of temporarily storing, recycling and purifying storm water; (2) Upgrading the traditional drainage system and improving the existing drainage protection standards; (3) Integrating natural drainage systems and water bodies (Chan et al. 2018).

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There are a few types of LID, such as biological drainage systems, rain water gardens, permeable sidewalks and green roofs etc. (Everett et al. 2015). Among these LID designs, the rain water garden was considered as the main solution to urban flooding problems in China (Wang et al. 2009). A rain water garden is a biological detention facility, which can effectively achieve natural purification of rain water. Compared with a large-scale municipal transformation, utilizing rain water gardens to improve waterlogging and runoff pollution is more practical. Rain water gardens can effectively reduce peak runoff and relieve the pressure of municipal drainage, and can also purify water quality, improve regional climate and the livability of the city. Meanwhile, some studies on rain water gardens focus on the filler performance. Li et al. (2007) reported that low cost filler materials, such as gravel and blast furnace slag, achieved great performance in terms of pollutant removal. Wu et al. (2010) studied the decontamination ability of zeolite, anthracite, shale and vermiculite in the vertical flow constructed wetland, and found that the treatment effect is better under high load. In addition, Deng et al. (2008) developed an integrated stormwater system on a GIS platform and a Storm Water Management Model (SWMM), to assist the visual design of LID facilities. Li et al. (2018) indicated that LID can mitigate the thermal impacts of urban stormwater runoff and alleviate resulting ecological problems. Based on these policies and studies, many cities started sponge city demonstration projects. Wuhan (Hubei Province) has completed a sponge city construction in Qingshan District and Hanyang New District, where the ‘breathing’ function of the sponge city was initially demonstrated (Wen & Liu 2018).

However, a rain garden on red soil has been rarely studied. The red soil areas in China usually have the largest annual rainfall, and red soil has poor permeability, agglomeration difficulty, low base saturation and low nutrients levels (He et al. 2008). Furthermore, red soil is the most widely distributed soil type in China, with a total area of 56.9 million hm², mostly in the vast low hills of the central Asian tropics between 25 and 31° north latitude. So it is important to study the performance of a rain garden constructed on red soil.

In this study we designed a series of experiments based on rainfall and soil conditions in Nanchang (Jiangxi Province), with an emphasis on red soil and local plants in rain garden designs. The study aims to obtain optimum rain garden design parameters, including a combination of filler ratio and plant type. Physical and chemical parameters including the permeability coefficient $K_{10}$ of the sponge and the pollutant removal rate were measured. These parameters were analyzed by using an analytic hierarchy process and comprehensive scoring method of orthogonal tests. Finally, an optimum sponge structure suitable for red soil was obtained, with pollutant removal rate quantified, which can provide guidance for the construction of a sponge city in red soil regions in China.

**MATERIALS AND METHODS**

**The study area**

The city of Nanchang is the capital city of Jiangxi Province. It is located in the north of central Jiangxi, on the southwest bank of Poyang Lake between 115°89′ and 116°35′ east longitude and between 28°10′ and 29°11′ north latitude (Figure 1). The whole area is dominated by plains, accounting for 35.8%.

![Figure 1](http://iwaponline.com/jwcc/article-pdf/12/2/371/865790/jwc0120371.pdf)
The southeast is relatively flat, the northwest hills are undulating, the water network is dense, with many lakes. The water area is 2,204.37 km², accounting for 29.78%. The annual rainfall is 1,600–1,700 mm with 147–157 precipitation days, an annual average of 5.6 rainstorm days and an annual average relative humidity of 78.5%. The city is dominated by red soil. Nanchang is a typical southern city that often experiences urban disasters, especially flood.

**Reagents**

Potassium dichromate (99.8%, AR), sodium hydroxide (96%, AR) and zinc sulfate heptahydrate (99.5%, AR), mercuric biniodide (99.5%, AR), L-ascorbic acid (99.7%, AR), potassium iodide (99.0%, AR), ammonium chloride (99.5%, AR), ammonium molybdate (99.0%, AR), silver sulfate (99.7%, AR), potassium dihydrogen phosphate (99.5%, AR), potassium sodium tartrate (99.0%, AR), potassium antimonyl tartrate (99.0%, AR), potassium peroxydisulfate (99.5%, AR), potassium hydrogen phthalate (99.8%, AR), ammonium iron (II) and sulfate hexahydrate (99.5%, AR), were all purchased from XiLong Scientific (Shantou, Guangdong, China).

**The experimental device and measurement method**

The main experimental device is shown in Figure 2. This device consists of an aquifer (50 mm), cover layer (50 mm), planting layer (150 mm), filler layer (650 mm) and drainage...
layer (100 mm), and it is separated by geotextiles between each layer. Simulation rain water flows out of the tank, through each layer, and finally flows out of the drain layer. Then the water sample is collected and determined by standard methods. In this study, permeability coefficient \( K_{10} \), chemical oxygen demand (COD), \( \text{NH}_3\text{-N} \) concentration and total phosphorus (TP) concentration were measured as representative physical and chemical indicators respectively. In order to improve the accuracy of the data, these indexes were analyzed using standard methods. GB7788-87 Determination of Forest Soil Permeability was used to measure the \( K_{10} \) for every sample, and Nessler Reagent Spectrophotometry GB7479-87 was used to obtain the \( \text{NH}_3\text{-N} \) concentration. TP concentration and COD were measured by Ammonium Molybdate Spectrophotometry GB11893-89 and Rapid Oven Method respectively.

**Preparation of simulated rain water**

The water quality of road runoff rain water in Qianhu campus of Nanchang University were reported as follows: 4.13–557.38 mg/L of COD, 0.01–2.41 mg/L of TP, and 0.04–5.29 mg/L of \( \text{NH}_3\text{-N} \) (Jiang 2013). Since the selected area had less pollution than the area in the literature, lower concentrations were used for simulated rainwater with 160 mg/L of COD, 1.20 mg/L of TP and 1.40 mg/L of \( \text{NH}_3\text{-N} \) by dissolving 1.2754 g potassium hydrogen phthalate, 0.5235 g ammonium chloride and 0.5308 g potassium dihydrogen phosphate were dissolved in 1 L water respectively.

In order to simulate true rainfall, we used Nanchang rainstorm intensity formula:

\[
q = \frac{1598(1 + 0.69 \log P)}{(t + 1.4)^{0.69}} = \frac{167A}{(t + 1.4)^{0.69}}
\]

(1)

where the value of \( P \) (recurrence interval) is 5. If \( A \) is defined as \( 9.57(1 + 0.69 \log P) \), then the value of \( A \) is 14.19 mm/h. Rainwater runoff was estimated using the following (Li et al. 2007):

\[
Q_{\text{simulation}} = A \cdot a \cdot k
\]

(2)

where \( A \) represents the rain force value when \( P \) is five years in Nanchang, \( a \) represents the instrument floor area of 600 cm\(^2\), and \( k \) represents the confluence area ratio of 20 (Zhang & Xu 2017). Then, \( Q_{\text{simulation}} \) of 4.75 mL/s is obtained and used in subsequent tests.

**Preparation of filler materials and plants**

Since filter materials are usually used in large quantities in the green space around roads, there should be sufficient supplies which are low cost and environmentally friendly. The six filler materials selected include perlite, coral sand, maifan stone, vermiculite, ceramsite and bio-charcoal (Ying & Zhao 2013). They were all purchased from a garden product market in Nanchang, and the physical properties of these fillers are listed in Table 1.

In addition, *Coreopsis drummondii* Torr et Gray, *Conyza Canadensis*(L.) Cronq, *Canna indica* L and *Arachis duranensis* were selected as tested plants. They were collected from Nanchang Hangkong University. Especially, in order to improve the reliability of this experiment, the plants were planted in prepared soil, which consisted of 65% sand, 30% red soil and 5% nutritious soil, a month in advance.

**Methods for data analysis**

**Analytic hierarchy process**

Multiple factors need to be considered during the screening of single fillers, however, the quality and importance of each factor is different. Such a multi-objective decision-making case can be solved by the analytic hierarchy process (Gao 2014). The analytic hierarchy process is a combination of qualitative and quantitative, systematic and hierarchical analysis methods with the following six steps:

| Physical properties of fillers |
|-----------------------------|
| Exterior | Particle size | Density | Porosity |
| Ceramsite | Spherical | 0.5–32 | 0.19 | 48.69 |
| Coral sand | Amorphous | 1–50 | 1 | – |
| Maifan stone | Granular | 1–6 | 2.55 | – |
| Vermiculite | Sheet | – | 0.52 | 64.38 |
| Perlite | Granular | 0.1–5 | 0.15 | – |
| Bio-charcoal | Granular | 0.8–6 | 0.8–0.85 | – |
(1) Divide the factors involved into several levels and establish a multi-level hierarchical model.

(2) According to the evaluation scale, the initial relative importance of each element of the same level is determined, and quantified, then the evaluation matrix A is established.

(3) Calculate the eigenvectors of the evaluation matrix and the corresponding maximum eigenvalues to determine the relative importance of each layer of elements.

(4) The consistency check of the matrix is performed, including the calculation of the consistency index (CI), the average random consistency index (RI), and the consistency ratio (CR). If CR < 0.1, then the consistency of the evaluation matrix is considered acceptable.

(5) If the above steps are passed and the consistency test is passed, the obtained feature vector is the weight of each factor.

(6) Combine the weights of various factors, and finally determine the total weight of the layer elements of the scheme to the target layer, and select the optimal filler according to the weight.

In the single filler screening experiment in the first step, the analytic hierarchy process was used to analyze the results, and the four fillers used in the combined experiment were screened, and then the next experiment was carried out.

**Comprehensive scoring method for multi-index orthogonal experiment**

The experiment of combined fillers was carried out by the Taguchi’s orthogonal array experiment with a five-factor four-level orthogonal experimental design, and the experimental results include four indexes as follows: permeability coefficient $K_{10}$, COD removal rate, TP removal rate and NH$_3$-N removal rate. The determination of the optimal combination of experiments depends on the interaction of the four indicators. This experiment used the ‘comprehensive scoring method’ to analyze the results (Yuan 2005).

The comprehensive scoring method includes conversion from multiple indicators to a single indicator and the application of extremum difference analysis. Specifically, consider the importance of each indicator and the measured values of the experiment, and then evaluate the results of each group of experiments as a comprehensive indicator. The key to this method is scoring. The scoring should not only take into account the importance of each indicator, but also consider the pros and cons of each indicator.

Generally speaking, the comprehensive scoring method is similar to the standardization process in the analytic hierarchy process, that is, the best value of each indicator is firstly set to the full score, the highest value is determined as the lowest score, and the other values are scored proportionally to the difference from the best value. Then add all the indicators of each group of experiments to the comprehensive score of the group of experiments. The method is simple and suitable for situations where the importance of each indicator is substantially equal.

**RESULTS AND DISCUSSION**

**Screening experiment and data processing analysis of a single filler in rain gardens**

**The analysis of permeability coefficient $K_{10}$**

Stable permeability coefficient $K_{10}$ of six alternative fillers was measured according to GB7788-87 Determination of Soil Permeability in Forests. The stable permeability coefficient curve of a single filler is shown in Figure 3 which indicated that each filler has reached saturation during the measurement, so the results are considered as representative. After removing the...
large deviation values in each set of data, the average value of the permeability coefficient K_{10} of each filler was obtained and compared, as shown in Figure 4. It can be seen from Figure 4 that the permeability coefficient from large to small is as follows: perlite > coral sand > maifan stone > vermiculite > ceramsite > biocharcoal. The high permeability coefficient of perlite is mainly due to its relatively uniform particle size (between 2 and 3 mm), porous surface lighter than water density. Coral sand has a large porosity and a porous surface, which may correlate to its penetration ability. Maifan stone is hard and does not swell after immersion, and its small porosity is the reason for the low permeability coefficient. Comparing vermiculite to ceramsite, vermiculite is smaller, its bulk density is larger but its permeability coefficient is greater. Mainly because the ceramsite texture is hard and light, a very strong extrusion phenomenon between the ceramsite was observed when it floats on the water surface after full immersion. It causes the porosity to decrease more sharply than in the partially immersed state, and results in a decrease in the permeability coefficient. Bio-charcoal has the lowest permeability coefficient, in spite of a strong adsorption capacity and great filtration effect.

**The analysis of pollutant removal effect**

In order to analyze the removal effect of COD, NH$_3$-N and TP by each filler, water samples were collected after 60 minutes and various chemical indicators were measured. The experimental data of each indicator is shown in Table 2.

All six fillers have certain purification abilities for simulating road rainwater. The removal rate of NH$_3$-N by various fillers is generally higher than that of TP and COD. This is consistent with previous reports, mainly attributed to the good adsorption properties of these materials for NH$_3$-N (Fu et al. 2011; Tian et al. 2012; Zhang 2012; Zheng et al. 2015).

**Screening and evaluation of fillers**

In this experiment, permeability coefficient, price and pollutant removal rate were selected for evaluation and analysis. Since the units of each indicator were different, it was difficult to compare directly, so it was necessary to standardize before comparison. The actual data of each indicator and the standardized results are shown in Tables 3 and 4.

The target layer is the ideal filler (A). The factors of the criterion layer are the permeability coefficient K$_{10}$ (B$_1$), the price (B$_2$), and the pollutant removal efficiency (B$_3$). The three factors of the scheme layer are COD removal rate (C$_1$), NH$_3$-N removal rate (C$_2$) and TP removal rate (C$_3$).

First, the hierarchical model was built, as shown in Figure 5. Then the relative importance of permeability coefficient K$_{10}$, price and pollutant removal efficiency were determined according to the 1–9 ratio scale method, as shown in Table 5.

So, a pairwise comparison matrix of three indexes (permeability coefficient K$_{10}$, price and pollutant removal efficiency) was obtained according to Table 5, as shown in Table 6.

![Figure 4](http://iwaponline.com/jwcc/article-pdf/12/2/371/865790/jwc0120371.pdf) | Comparison of average permeability coefficients K10 of various fillers.
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**Table 2 | Data of single filler removal results**

| Species          | Perlite | Coral sand | Maifan stone | Vermiculite | Ceramsite | Bio-charcoal |
|------------------|---------|------------|--------------|-------------|-----------|-------------|
| COD removal rate (%) | 4.6     | 9.6        | 9.6          | 4.6         | 4.6       | 9.6         |
| NH$_3$-N removal rate (%) | 31.6    | 40.2       | 57.3         | 65.8        | 31.6      | 31.6        |
| TP removal rate (%)       | 2.3     | 2.3        | -12.8        | 2.3         | 2.3       | 9.8         |

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Table 3 | Actual data of each evaluation index

| Permeability coefficient $K_{10}$ (mm/s) | 1/price (¥/l) | COD removal rate (%) | NH$_2$-N removal rate (%) | TP removal rate (%) |
|----------------------------------------|---------------|----------------------|--------------------------|---------------------|
| Ceramsite                              | 1.64          | 1/567                | 4.6                      | 31.6                | 2.3                 |
| Coral sand                             | 2.16          | 1/1600               | 9.6                      | 40.2                | 2.3                 |
| Maifan stone                            | 2.01          | 1/8000               | 9.6                      | 57.3                | -12.8               |
| Vermiculite                            | 1.74          | 1/650                | 4.6                      | 65.8                | 2.3                 |
| Perlite                                | 2.17          | 1/400                | 4.6                      | 31.6                | 2.3                 |
| Bio-charcoal                           | 1.47          | 1/6000               | 9.6                      | 31.6                | 9.8                 |

Table 4 | Standardization of target data

| Permeability coefficient $K_{10}$ (mm/s) | 1/price (¥/l) | COD removal rate (%) | NH$_2$-N removal rate (%) | TP removal rate (%) |
|----------------------------------------|---------------|----------------------|--------------------------|---------------------|
| Best value                             | 2.17 (1)      | 1/400 (1)            | 9.6 (1)                  | 65.8 (1)            | 9.8 (1)             |
| Worst value                            | 1.47 (0)      | 1/8000 (0)           | 4.6 (0)                  | 31.6 (0)            | -12.8 (0)           |
| Ceramsite                              | 0.24          | 0.69                 | 0.00                     | 0.00                | 0.67                |
| Coral sand                             | 0.99          | 0.21                 | 1.00                     | 0.25                | 0.67                |
| Maifan stone                            | 0.77          | 0.00                 | 1.00                     | 0.75                | 0.00                |
| Vermiculite                            | 0.39          | 0.60                 | 0.00                     | 1.00                | 0.67                |
| Perlite                                | 1.00          | 1.00                 | 0.00                     | 0.00                | 0.67                |
| Bio-charcoal                           | 0.00          | 0.18                 | 1.00                     | 0.00                | 1.00                |

Figure 5 | Hierarchical model.

Table 5 | 1–9 ratio scale method

| Scaling | Definition (comparing factors $i$ and $j$) |
|---------|-------------------------------------------|
| 1       | Factors $i$ and $j$ are equally important |
| 3       | Factor $i$ is slightly more important than $j$ |
| 5       | Factor $i$ is more important than $j$ |
| 7       | Factor $i$ is strongly important than $j$ |
| 9       | Factor $i$ is absolutely more important than $j$ |
| 2, 4, 6, 8 | Intermediate value of two adjacent degrees |
| Reciprocal | Comparison factors $j$ and $i$ |

Table 6 can be converted into an evaluation matrix:

$$
A = \begin{bmatrix}
1 & 0.33 & 2 \\
3 & 1 & 5 \\
0.5 & 0.2 & 1
\end{bmatrix}
$$

Add the three columns of the matrix to obtain the sum matrix:

$$
\begin{bmatrix}
3.33 \\
9 \\
1.7
\end{bmatrix}
$$
An eigenvector $W$ of the matrix $A$ (approximate) can be obtained by nominalizing the above matrix with its sum:

$$W = \begin{bmatrix} 3.33/14.03 \\ 9/14.03 \\ 1.7/14.03 \end{bmatrix} = \begin{bmatrix} 0.238 \\ 0.641 \\ 0.121 \end{bmatrix}$$

The evaluation matrix $A$ and the eigenvector $W$ product were:

$$AW = \begin{bmatrix} 1 & 0.33 & 2 \\ 3 & 1 & 5 \\ 0.5 & 0.2 & 1 \end{bmatrix} \begin{bmatrix} 0.24 \\ 0.64 \\ 0.12 \end{bmatrix} = \begin{bmatrix} 0.693 \\ 1.960 \\ 0.368 \end{bmatrix}$$

Since $W$ is an approximate eigenvector of $A$, $AW$ is not a multiple of $W$. The average of the sum of the ratios of the corresponding elements of matrix $AW$ and matrix $A$ is taken as the approximate eigenvalue, the maximum eigenvalue of matrix $A$ was obtained:

$$\lambda_{\text{max}} = \frac{1}{3} \left( \frac{0.693}{0.238} + \frac{1.960}{0.641} + \frac{0.368}{0.121} \right) = 3.004$$

After $\lambda_{\text{max}}$ is calculated, the consistency check of evaluation matrix $A$ can be performed.

First, the consistency indicator (CI) is calculated:

$$\text{CI} = \frac{\lambda_{\text{max}} - n}{n-1} = \frac{3.004 - 3}{2} = 0.002$$

Then, since the order of $A$ was 3, the average random consistency index (RI) is obtained according to Table 7.

RI = 0.58

Finally, calculate the consistency ratio based on CI and RI:

$$\text{CR} = \frac{\text{CI}}{\text{RI}} = \frac{0.002}{0.58} = 0.0034$$

Since CR is <0.1, the consistency of the evaluation matrix passed the test, meaning feature vector $W$ represented the weight of the three factors: permeability coefficient $K_{10}$, price and pollutant removal efficiency.

After completing the weight analysis of the criterion layer to the target layer, the weight of the pollutant removal efficiency of the three factors in the scheme layer is analyzed. The evaluation matrix is shown in Table 8.

Similarly:

$$B = \begin{bmatrix} 1 & 7 & 8 \\ 0.143 & 1 & 2 \\ 0.125 & 0.5 & 1 \end{bmatrix}$$

Find the eigenvectors of the evaluation matrix $B$ (the calculation process is the same as before):

$$W_1 = \begin{bmatrix} 0.770 \\ 0.151 \\ 0.079 \end{bmatrix}$$

The product of the evaluation matrix $B$ and the eigenvector $W_1$ is:

$$BW_1 = \begin{bmatrix} 1 & 7 & 8 \\ 0.143 & 1 & 2 \\ 0.125 & 0.5 & 1 \end{bmatrix} \begin{bmatrix} 0.770 \\ 0.151 \\ 0.079 \end{bmatrix} = \begin{bmatrix} 2.459 \\ 0.419 \\ 0.251 \end{bmatrix}$$

### Table 6 | Comparison of the criteria layer factors to the target pairwise comparison matrix

| For A | B_1 | B_2 | B_3 |
|-------|-----|-----|-----|
| B_1   | 1   | 1/3 | 2   |
| B_2   | 3   | 1   | 5   |
| B_3   | 1/2 | 1/5 | 1   |

### Table 7 | Average random consistency indicator

| Order | 3   | 4   | 5   | 6   | 7   | 8   | 9   | 10  | 11  | 12  | 13  | 14  |
|-------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| RI    | 0.58| 0.89| 1.12| 1.26| 1.36| 1.41| 1.46| 1.49| 1.52| 1.54| 1.56| 1.58|
The maximum eigenvalue of matrix \( B \) is obtained as follows:

\[
\lambda_{\text{max}} = \frac{1}{3} \left( 2.459 + 0.419 + 0.251 \right) = 3.0485
\]

As before, after the \( \lambda_{\text{max}} \) is calculated, a consistency check of evaluation matrix \( B \) can be performed:

\[
\text{CI} = \frac{\lambda_{\text{max}} - n}{n-1} = \frac{3.0485 - 3}{2} = 0.02425
\]

Utilize Table 7 to obtain the average consistency index \( \text{RI} = 0.58 \).

Finally, calculate the consistency ratio based on CI and \( \text{RI} \):

\[
\text{CR} = \frac{\text{CI}}{\text{RI}} = \frac{0.02425}{0.58} = 0.0418
\]

The total score of the materials is ranked from high to low as perlite > ceramsite > vermiculite > coral sand > maifan stone > bio-charcoal. The top four fillers are used as fillers for combined experiments to find the combination of high permeability and pollutant removal capacity.

### Screening experiment and data processing analysis of combined filler experiments

In order to obtain objective and accurate experimental results, we designed a five-factor four-level orthogonal experiment, \( L_{16}(4^5) \), with factors and levels of the experiment shown in Table 11, and the experimental arrangement is shown in Table 12. The orthogonal experiment is an effective way to determine the optimum conditions among many factors (Shao et al. 2019).

**Composite filler design and its permeability coefficient and removal effect**

When the permeability coefficient \( K_{10} \) was measured, plant factors were not considered. The experimental procedure
was consistent with the determination method of the permeability coefficient $K_{10}$ of single filler material. Photographs of the experiment are shown in Figure 6.

The filler was cleaned and dried before each experiment, then all experiments were carried out according to Table 12, an orthogonal test table, which is based on the orthogonality to select some representative points from the comprehensive test. Then, according to Equations (1) and (2), rainwater runoff simulation flow $q$ is 4.73 mL/s. All experiments were carried out in the device shown in Figure 2. Finally, in each experiment, a 1 L water sample was collected and measured after 60 minutes.

### Analysis of results

The permeability coefficient $K_{10}$ of the combined filler is shown in Figure 7. In general, the composite filler had a lower permeability coefficient $K_{10}$ than the single filler, and this was due to different fillers stacked together which led to an increase in bulk density and a decrease in porosity. In addition, in the 16 orthogonal experiments, only three groups of experiments had a permeability coefficient $K_{10}$ greater than 1. Interestingly, the proportion of coral sand was more than 30% in these three groups of experiments, indicating the higher the content of coral sand, the better the permeability coefficient $K_{10}$ of the sponge body, but excessive coral sand can affect plant growth. Similarly, when the proportion of vermiculite and perlite was high, the permeability coefficient of the sponge was very low, however, the removal of pollutants performed better. On the other hand, the thickness of the sponge body also affected the permeability coefficient $K_{10}$. The thickness of the first and fourth groups of sponges was 20 cm (thinnest) and 65 cm (thickest), respectively, and they all had poor permeability coefficients $K_{10}$. When the thickness of the sponge was 45–55 cm, the permeability coefficient $K_{10}$ of the sponge was high.

In order to obtain the optimal sponge structure, the permeability coefficient $K_{10}$ and contaminant removal capacity of the sponge must be considered at the same time. In the study, a comprehensive scoring method for the multi-index orthogonal experiment was adopted.

First, according to the results of orthogonal experiments, as is shown in Table 13, we know the optimal and worst value for each indicator, and the optimal value is marked as 10 points, with the worst value marked as 1 point; other values are calculated according to their proportion of the difference between the optimal value and the worst value. Second, when calculating the composite score, stipulate the weight of the permeability coefficient $K_{10}$ as 2, and other indicators are 1. So, a comprehensive score is the sum of $2 \times$ permeability coefficient $K_{10} +$ COD removal

| Table 11 | Factor level table |
|---|---|
| Factors | Level Ceramsite Vermiculite Perlite Coral sand Plant species |
| 1 | 5 5 5 5 Coreopsis drummondii Torr et Gray |
| 2 | 10 10 10 10 Conyza Canadensis (L.) Cronq |
| 3 | 15 15 15 15 Canna indica L |
| 4 | 20 20 20 20 Arachis duranensis |

The units of factors are ‘cm’, except the plant species.

| Table 12 | Orthogonal experiment combination table |
|---|---|
| Group/level | Factor/level |
| 1 | 1 1 1 1 1 |
| 2 | 1 2 2 2 2 |
| 3 | 1 3 3 3 3 |
| 4 | 1 4 4 4 4 |
| 5 | 2 1 2 3 4 |
| 6 | 2 2 1 4 3 |
| 7 | 2 3 4 1 2 |
| 8 | 2 4 3 2 1 |
| 9 | 3 1 3 4 2 |
| 10 | 3 2 1 3 1 |
| 11 | 3 3 4 2 4 |
| 12 | 3 4 2 1 3 |
| 13 | 4 1 4 2 3 |
| 14 | 4 2 3 1 4 |
| 15 | 4 3 2 4 1 |
| 16 | 4 4 1 3 2 |
rate + NH$_3$-N removal rate + TP removal rate. The analysis results are shown in Table 14.

Now, the orthogonal experiment of multiple indicators is summarized as a single index, and the analysis results of the single index are shown in Table 15.

As can be seen from the above table, the R value (from high to low) is in the order R$_{plant}$ species > R$_{vermiculite}$ > R$_{ceramsite}$ > R$_{perlite}$ > R$_{coral sand}$. For the plant species, K3 is the highest (33.68), suggesting *Canna indica L* is the best plant. Similarly, the optimal levels of filler depth are found as follows: vermiculite = 10 cm, ceramsite = 15 cm, perlite = 15 cm and coral sand = 20 cm. In summary, the optimal
The sponge structure is vermiculite (10 cm) + ceramsite (15 cm) + perlite (15 cm) + coral sand (20 cm) + *Canna indica* L. Performance tests of optimal sponge were carried out, and the results are shown in Table 16.

For the optimal sponge structure, as much as 96.6% of NH$_3$-N can be removed, and the permeability coefficient $K_{10}$ is up to 1.2. The results suggest that this analytical method is very reliable in selecting the factors.

### CONCLUSIONS

In this paper, a high NH$_3$-N removal urban sponge was designed for application in red soils, which consisted of 15 cm ceramsite + 10 cm vermiculite + 15 cm perlite + 20 cm coral sand with *Canna indica* L. Performance indicators of the optimal sponge are as follows: the permeation coefficient, $K_{10}$, of 1.20 mm/s, with an NH$_3$-N removal rate of 96.6%, a TP removal rate of 36.8%, and a chemical oxygen demand removal rate of 9.6%. The results showed that the urban sponge designed in this experiment not only has excellent permeability, but it can also effectively remove contaminants in runoff rain water. The whole design and selection process can be very helpful for the construction of an urban sponge city in red soil areas in southern China and other red soil areas in the world.

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### REFERENCES

Chan, F. K. S., Griffiths, J. A., Higgitt, D., Xu, S., Zhu, F., Tang, Y. T. & Thorne, C. R. 2018 ‘Sponge city’ in China – a breakthrough of planning and flood risk management in the urban context. *Land Use Policy* **76**, 772–778.

Deng, S., Zhang, X., Shao, Z., Yan, W., Chai, H. & He, Q. 2018 An integrated urban stormwater model system supporting the
The whole life cycle of Sponge city construction programs in China. *J. Water Clim. Change* **102** (2), 298–312.

Everett, G., Lamond, J., Morzillo, A. T., Chan, F. K. S. & Matsler, A. M. 2015 Sustainable drainage systems: helping people live with water. *Proc. ICE-Water Manage.* **169** (2), 94–104.

Fu, K., Xia, Q. B., Li, Z. & Zhong, T. C. 2011 Research of ammonia adsorption with mafian stone. *Ind. Saf. Environ. Prot.* **37** (4), 3–5.

Gao, X. L. 2014 *Study on Filler in Road Rainwater Bioretention System*. ME Thesis, Taiyuan University of Technology, Taiyuan, China.

He, J. Z., Zheng, Y., Chen, C. R., He, Y. Q. & Zhang, L. M. 2008 Microbial composition and diversity of an upland red soil under long-term fertilization treatments as revealed by culture-dependent and culture-independent approaches. *J. Soils Sediments* **8** (5), 349–358.

Jiang, Y. Y. 2015 *Urban Catchment Rainfall Runoff Pollution Characteristics and Control Simulation*. ME Thesis, Nanchang University, Nanchang, China.

Jiang, Y., Zevenbergen, C. & Ma, Y. 2018 Urban pluvial flooding and stormwater management: a contemporary review of China’s challenges and ‘sponge cities’ strategy. *Environ. Sci. Policy* **80**, 132–143.

Li, H. Z., Ye, J. F. & Xu, Z. X. 2007 Analysis on removal efficiency of pollutants by some substrates in vertical-flow constructed wetland. *China Water Wastewater* **23** (19), 27.

Li, J., Gong, Y., Li, X., Yin, D. & Shi, H. 2018 Urban stormwater runoff thermal characteristics and mitigation effect of low impact development measures. *J. Water Clim. Change* **10** (1), 53–62.

Liao, C. X., Gao, A. G. & Huang, E. H. 2016 Enlightenment of rainwater management in foreign countries to sponge city construction in China. *Water Resour. Prot.* **32** (1), 42–45.

Mitchell, G. 2005 Mapping hazard from urban non-point pollution: a screening model to support sustainable urban drainage planning. *J. Environ. Manage.* **74** (1), 1–9.

Morison, P. J. & Brown, R. R. 2011 Understanding the nature of publics and local policy commitment to Water Sensitive Urban Design. *Landscape Urban Plan.* **99** (2), 83–92.

Pyke, C., Warren, M. P., Johnson, T., LaGro Jr., J., Scharfenberg, J., Groth, P. & Main, E. 2011 Assessment of low impact development for managing stormwater with changing precipitation due to climate change. *Landscape Urban Plan.* **103** (2), 166–173.

Qiu, B. X. 2015 The connotation, ways and prospects of sponge city. *China Invest. Des.* **7**, 1–7.

Shao, Q., Lu, M. M., Zhou, J. C., Zhu, Z. F. & Song, Y. Q. 2019 Preparation of non-sintered fly ash filter (NSFF) for ammonia nitrogen adsorption. *Environ. Technol.* **40** (15), 1988–1999.

Tian, L., Kong, Q. & Ren, Z. M. 2012 Adsorption characteristics of bio-charcoal and zeolite and their biological regeneration. *Chin. J. Environ. Eng.* **6** (10), 3424–3428.

Voyde, E., Fassman, E. & Simcock, R. 2010 Hydrology of an extensive living roof under sub-tropical climate conditions in Auckland, New Zealand. *J. Hydrol.* **394** (3–4), 384–395.

Wang, S. F., Yang, L. & Bai, W. L. 2009 Perfect combination of art and technology – study on the construction of rain garden. *Chin. Landscape Archit.* **6**, 54–57.

Wang, H., Mei, C., Liu, J. & Shao, W. 2018 A new strategy for integrated urban water management in China: Sponge city. *Sci. China Technol. Sci.* **61** (3), 317–329.

Wen, J. G. & Liu, H. M. 2018 The technical approach and main problems of the design of ‘sponge city’ in the new era – taking the metropolis Wuhan as an example. *City Observ.* **3**, 121–130.

Wu, J., Wang, R., Xu, D., Zhang, X., He, F. & Wu, Z. 2010 Long term performance of pilot-scale vertical flow constructed wetland using different substrates. *China Environ. Sci.* **30** (5), 633–638.

Wu, D. J., Zhan, S. Z. & Li, Y. H. 2016 New trends and practical research on the sponge cities with Chinese characteristics. *China Soft Sci.* **1**, 79–97.

Ying, L. H. & Zhao, H. X. 2017 Summary of the structure and substrates purification performance in rain garden. *Chin. Landscape Arch.* **33** (5), 106–111.

Yuan, Y. F. 2005 Analysis of multi-target orthogonal experiment. *J. Hubei Auto. Ind. Inst.* **19** (4), 53–56.

Zhang, J. P. 2012 The application and research of vermiculite in nitrogen removing technology. *Environ. Monit. Forewarn.* **4** (5), 43–49.

Zhang, M. D. & Xu, H. S. 2017 Study on the effect of decontamination structure of runoff in rain garden in Nanjing. *Anhui Arch.* **6**, 11–14.

Zheng, Y. Y., Yu, Y. F., Li, Y., Wu, C. S., Liu, W. W. & Liu, C. Q. 2015 Adsorption of phosphorus on NH3-N by ceramsite made from waterworks sludge. *Chin. J. Environ. Eng.* **9** (2), 756–762.

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