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# Hydraulic conductivity and phosphorus adsorption preference of various waste bricks used as storm-water bio-filter media

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**ABSTRACT**

Urbanization can generate large amounts of construction waste including waste bricks, in which there are few suitable methods to solve. Thus, in this study, three common waste bricks were used as potential media for bioretention bonds. The hydraulic conductivity and phosphorus adsorption capacity of the waste bricks used were discussed. The results show that the hydraulic conductivity of the waste bricks decreased with the increase in added soil. When the phosphorus concentration was 5 mg/L, the adsorption rate of waste bricks with a size of less than 1 mm (red bricks, concrete blocks, and burn-free bricks) was 1%, 66%, 91.8%, respectively. The adsorption experiments proved that the adsorption rate of the three types of waste bricks does not change with the change in size. However, the adsorption capacity of red brick is proportional to the particle size, whereas the other bricks decrease with the increase in particle size. Such performances illustrate that waste bricks are effective materials that are used in bio-filter systems, and that a new approach regarding the treatment and disposal of construction and demolition waste in urban areas was found.

*Keywords:* Application potential; Hydraulic conductivity; Phosphorus adsorption; Waste bricks

## 1. Introduction

Nonpoint source pollution has become a serious issue in urban aquatic environments with rapid urbanization, particularly in developing countries. Hence, a great number of treatment practices have been proposed and applied to treat diverse levels of diffuse pollution worldwide [1,2]. Storm-water bio-filters have been widely applied as an effective and low-cost technology [3–5]. Such filters operate by filtering the runoff through a vegetated vertical filtration system [6]. This technique can solve the storm-water runoff problem by reducing the volume, and improving the water quality simultaneously through hydrological, physical, biological, and chemical processes [7].

The capacity of absorption and infiltration of the media used plays an important role in determining the performance of the bio-filter [8].

Many types of media, such as recycled rubber (e.g., tire crumb), scrap iron (e.g., zero-valent iron, iron-oxides), scrap wood (e.g., wood chips), industrial by-products (e.g., coconut coir, high-carbon wood ash, biochar), and waste biomass (e.g., biochar) have been tested and used in bio-filter systems [9–13].

However, published studies have simply focused on the treatment performance variation of pollutants (e.g., nitrogen, turbidity, chemical oxygen demand (COD), and, heavy

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metals) [14–17] caused by the different design and operating conditions, and few studies have investigated the permeation of a filter alone, which determines whether the system is sustainable. Currently, studies on infiltration systems only consist of a mix of dried sand of different sizes [14] or the addition of other metals to traditional sand [18]. In fact, we cannot ignore the fact that the hydraulic conductivity of the material has a direct impact on the infiltration effect of the bio-filter.

However, urbanization inevitably generates a large amount of construction and demolition (C & D) waste [19], and Yaqub estimated that the EU can generate approximately 180 million tons per year of C & D waste [20]. According to a survey, over 150 million tons of C & D waste has been produced per year in China, and C & D waste has become one of the most negative impacts of Chinese urbanization, which has received increasing attention by the government [21].

Some studies have focused on recycled construction waste, including the reclamation chain [22], the utilization of C & D waste as recycled aggregates in concrete [23], and the reproduction of concrete blocks [24]. Few studies have been conducted to test the application potential of C & D waste as a filter medium in bio-retention. Therefore, in this study, a new attempt is made to the reuse bricks in a bio-filter, reflecting the concept of waste recycling.

At the same time, an ideal bio-filter not only has to remove contaminants effectively, it must also ensure that the system is cost-effective, the material sources can easily be acquired, and that the system itself can be sustainable [25]. Therefore, in the choice of filler requires both hydraulic conductivity and good adsorption.

Considering all of the above aspects, the objective of our study is to access the hydraulic characteristics of different waste bricks, indicate the possibility of their application, provide optimal materials, and identify the optimal size.

## 2. Materials and methods

### 2.1. Waste bricks used

In this article, three types of C & D waste including red bricks, concrete blocks, and burn-free bricks were selected (see Fig. 1). The wastes bricks were divided into different sizes, namely, <1, 1–3, and 3–5 mm.

The chemical composition of the three kinds of bricks was determined through an energy dispersive X-ray analysis (EDAX). The specific surface area of the waste bricks was measured using an Autosorb-IQ automatic gas adsorption instrument. At the same time, we also observed the morphology of the three kinds of waste bricks used through scanning electron microscope (SEM).

### 2.2. Hydraulic measurements

In this study, the hydraulic conductivity was applied to represent the infiltration capacity of the various types of waste bricks. The hydraulic conductivity at saturation (*K*s) of the sample was measured using a constant head method at a laboratory [26], which used a direct application of Darcy's law. Based on the quantity of water, the length of the sample, the cross-sectional area of the sample, the time required to


Fig. 1. Photographs of selected C & D bricks: (a) red bricks, (b) concrete blocks, and (c) burn-free bricks.

drain the water, and the difference in the constant head [27], the following is obtained:

$$k = \frac{q \times l}{A \times \Delta h} \quad (1)$$

where $q$ is the mean infiltrate flow, $l$ is the height of filter media, $A$ represents the area of the cross section, and $\Delta h$ is the head loss of the cross section.

The configuration of the experimental setup is shown in Fig. 2. The filter columns were composed of a 3.4 cm diameter polyvinyl chloride pipe, with a sufficient depth to hold 30 cm of the difference in head, which consists of the 20 cm depth of the filter media and 10 cm depth of the flowing water. At the bottom, an outflow collection port is applied, and we use a beaker to completely collect the outflow.

The experimental process can be described as follows. Each experiment ensured that the inflow was stably controlled, and the experiment time was recorded from the beginning of the first water addition to the columns up to a certain collected value.

Considering the practical application, different ratios of waste bricks and natural soil (fraction bricks of 25%, 50%, 75%, and 100%) were set for each type of brick. In addition, the hydraulic conductivity of natural soil was also determined as a control for a comparison with the wastes bricks.

The hydraulic performance of nonvegetated storm-water filter media consisting of particles of less than 5 cm in size has not been tested; however, such media are frequently used in proprietary storm-water systems [18,28]. Therefore, we measured waste bricks with particles sized between 0 and 5 mm to confirm whether such media can be applied to a bio-filter.

Waste bricks can be used directly in the drainage layer. An estimated formula is as follows [29]:

$$M = H \times F \times m_1 \times 5\% \quad (2)$$

where $M$ stands for the total mass of the materials required in the bio-retention; $H$ represents the height of the required materials in the bio-retention; $F$ represents the catchment and

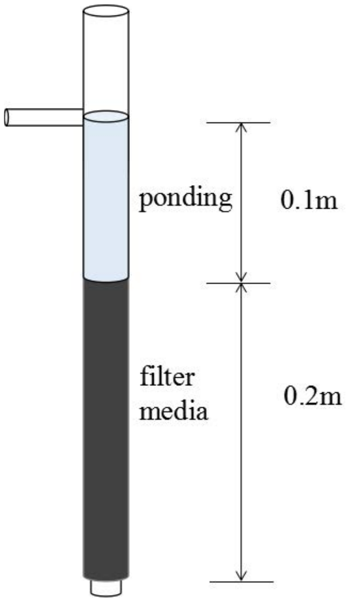


Fig. 2. Experimental infiltration columns.

area of bio-retention, where the catchment ratio is generally 5%; and $m_1$ signifies the mass of the material required per unit volume.

The calculation formula of the adsorption capacity is as follows:

$$Q_e = \frac{C_0 - C_e}{m_2} \times V \tag{3}$$

where $Q_e$ stands for the adsorption capacity, $V$ represents the adsorbate solution volume, $C_0$ indicates the initial mass concentration of the adsorbate in the solution, $C_e$ represents the residual mass concentration of the adsorbate during adsorption equilibrium, and $m_2$ is the sample quality.

The calculation formula of the phosphate adsorption rate is as follows:

$$R = \frac{C_0 - C_e}{C_0} \times 100\% \tag{4}$$

where $R$ stands for the phosphate adsorption rate, $C_0$ represents the initial mass concentration of the adsorbate in a solution, and $C_e$ represents the residual mass concentration of the adsorbate during a state of adsorption equilibrium.

## 3. Results and discussion

### 3.1. Morphology and composition

The morphologies of the three types of waste bricks used were investigated, the results of which are shown in Fig. 3. It can be seen in Fig. 3a that red bricks have uniformly distributed particles with sharp edges. It was found that many pores emerge in red bricks. From Fig. 3b it can be seen that concrete blocks have larger particles and a coarse exterior; in addition, a rounded edge is obtained. Beyond the edge, the pores can be found, which illustrates that concrete blocks have an uneven particle distribution. The morphology of burn-free bricks is similar to that of concrete blocks, and such bricks also have an uneven particle distribution and a rough particle surface. As shown in Fig. 3, the burn-free bricks have the largest pore space.

It has been reported that different surface morphologies can result in different pathways and adsorption capacities when used in a bio-filter. The relatively smooth surface of red bricks leads to a lower infiltration, and results in worse adsorption capacity pollutants. In contrast, concrete blocks and burn-free bricks have a good effect in terms of pollutant removal. However, if the particle size of the material is smaller, the infiltration will be reduced and the end result is clogging [30].

The specific surface area is 23, 20, and 52, respectively, for red bricks, concrete blocks, and burn-free bricks (Table 1). Compared with other materials, all three types of waste bricks have a relatively large specific surface area, indicating that they have a good contaminant adsorption capacity [31].

The composition of the bricks was determined (Table 1). The results indicated that the red bricks are composed of $SiO_2$ (72.63%) and $AlPO_4$ (27.37%), the concrete blocks consist of $CaCO_3$ (42.58%) and calcite (55.52%), and the burn-free bricks are composed of $SiO_2$ (38.66%), $AlPO_4$ (25.4%), and calcite (29.8%). These metal ions and their hydrates and oxides in bricks can form barely soluble compounds with phosphate precipitation. Owing to the existence of calcite, such materials are suitable to for sintering [31].

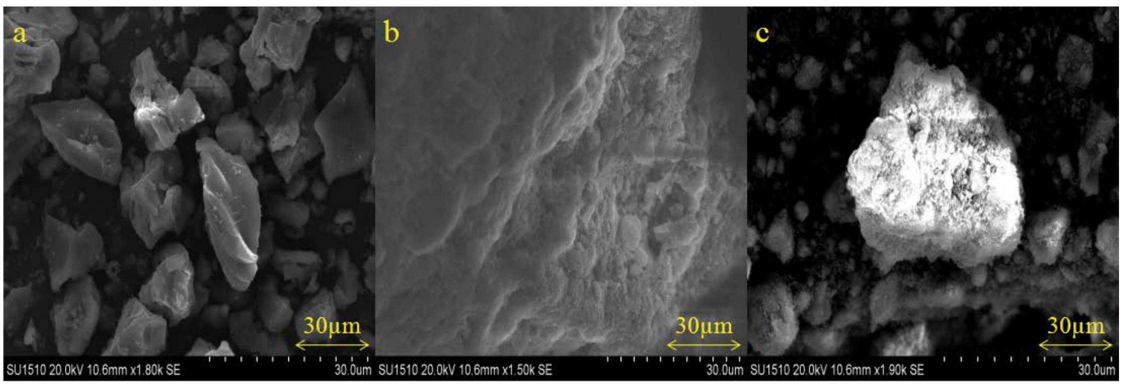


Fig. 3. SEM photographs of selected samples: (a) red bricks, (b) concrete blocks, and (c) burn-free bricks.

Table 1
Composition and surface area of materials

| Materials | Composition (%) | | | | | | Surface area ($m^2 g^{-1}$) |
|---|---|---|---|---|---|---|---|
| | $SiO_2$ | $AlPO_4$ | $CaCO_3$ | Calcite | | | value |
| | | | | $Mg_{0.03}Ca_{0.97}CO_3$ | $Ca(CO_3)$ | $Mg_{0.06}Ca_{0.94}CO_3$ | |
| Red bricks | 71.63 | 26.37 | – | – | – | – | 23.568 |
| Concrete blocks | – | – | 42.58 | 16.43 | 19.19 | 19.9 | 20.284 |
| Burn-free bricks | 38.66 | 25.4 | – | 9.8 | 10.1 | 9.9 | 52.23 |

*3.2. Hydraulic Conductivity of bricks*

The pore volume is also an important factor affecting the filtration capacity of the medium, and was determined for the different bricks, as shown in Fig. 4.

Previous studies have shown that different pore volumes of a flow have an influence on the hydraulic conductivity of different layer filters. This is due to diverse saturated water contents in different layers [32]. Taking into account that such materials will be applied to a bio-filter, every layer should use diverse particles.

The hydraulic conductivity of the three types of waste bricks was tested, the results of which are shown in Figs. 5 and 6. Different particle sizes of the materials show the same upward increasing trend. Different particle sizes of the red bricks are shown in Figs. 5a and 6a. The mean hydraulic conductivity of the different fractions (25%, 50%, 75%, and 100%) of red bricks with a particle size of less than 1 mm is $1.09 \times 10^{-3}$, $1.42 \times 10^{-3}$, $1.54 \times 10^{-3}$, and $7.01 \times 10^{-3}$ cm/s. The size range from 1 to 3 mm is $1.83 \times 10^{-3}$, $2.48 \times 10^{-2}$, 0.395, and 1.86 cm/s. The hydraulic conductivity of the soil filter media tested in this experiment is $3.63 \times 10^{-3}$ cm/s. Clearly, the hydraulic conductivity of red bricks with larger particle sizes has been increased one-hundred times. Marked reductions in the hydraulic conductivity were observed after

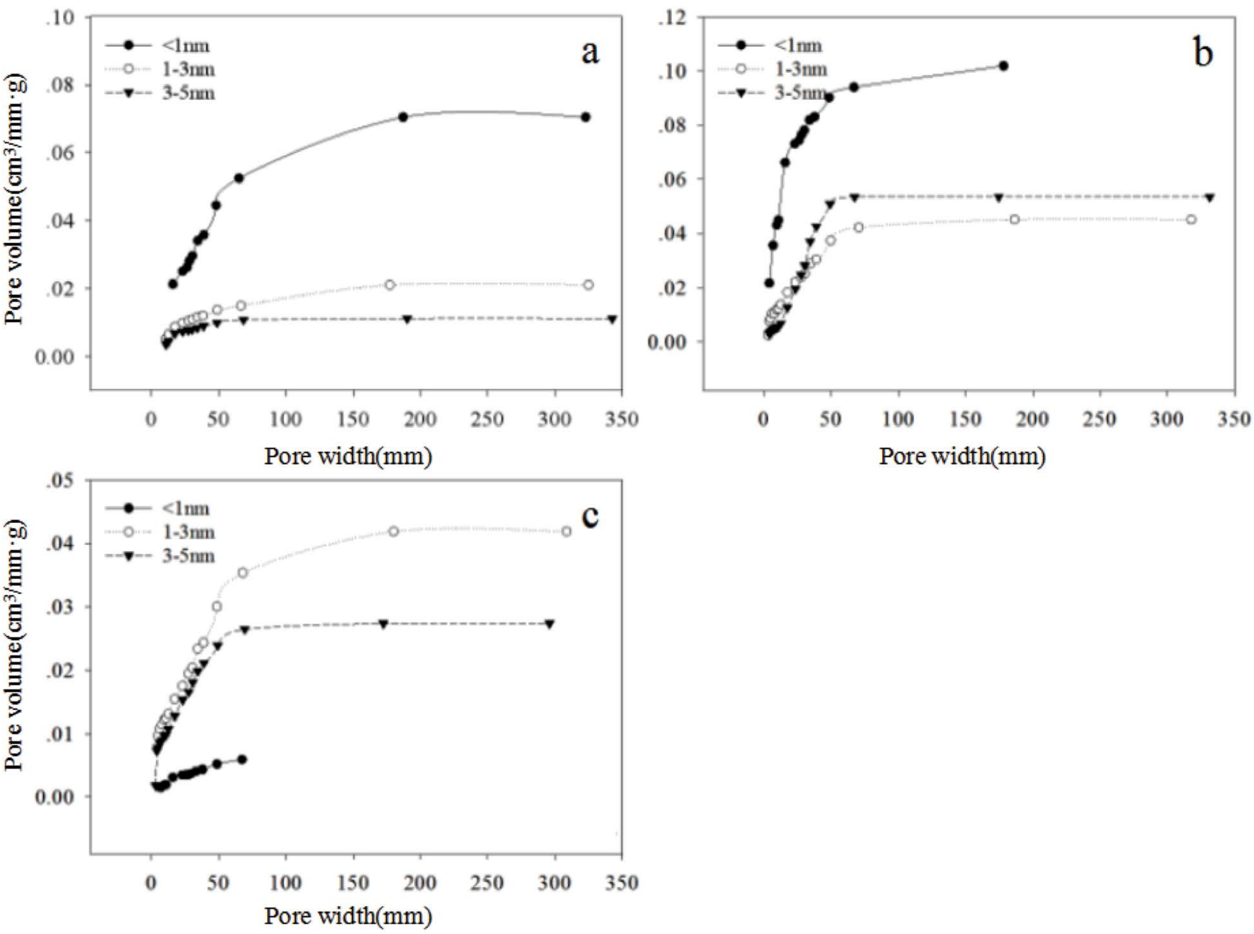


Fig. 4. The pore size distribution curves of selected samples: (a) red bricks, (b) concrete blocks, and (c) burn-free bricks.

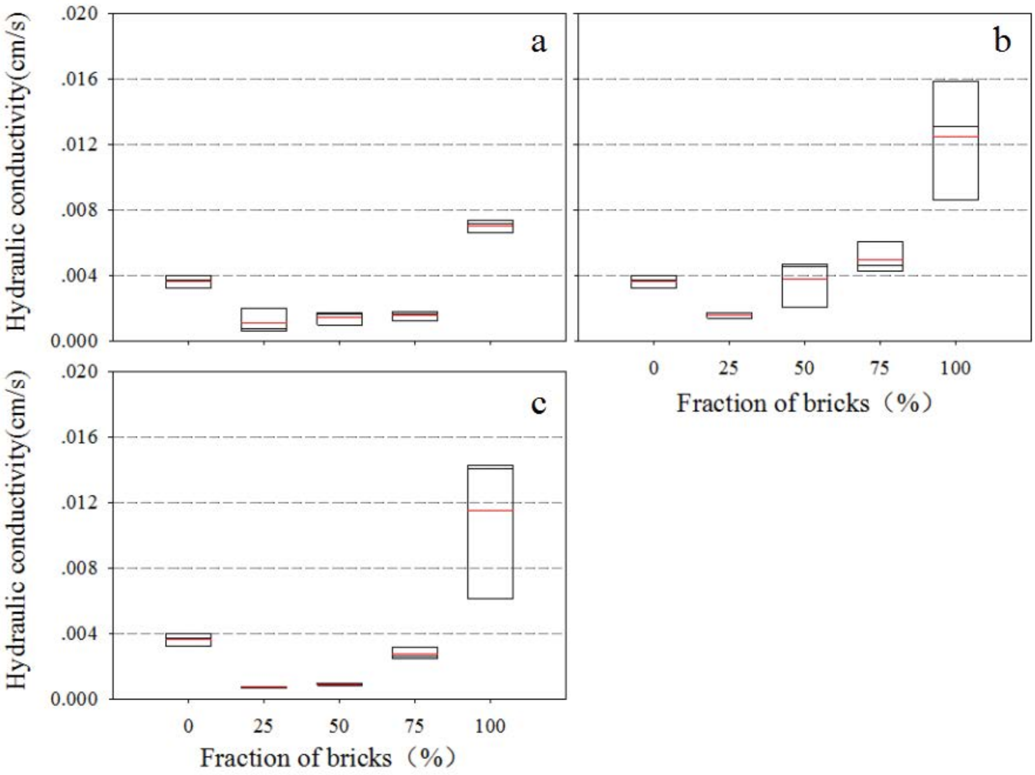


Fig. 5. Hydraulic conductivity of waste bricks with a size of <1 mm: (a) red bricks (b) concrete blocks, and (c) burn-free bricks.

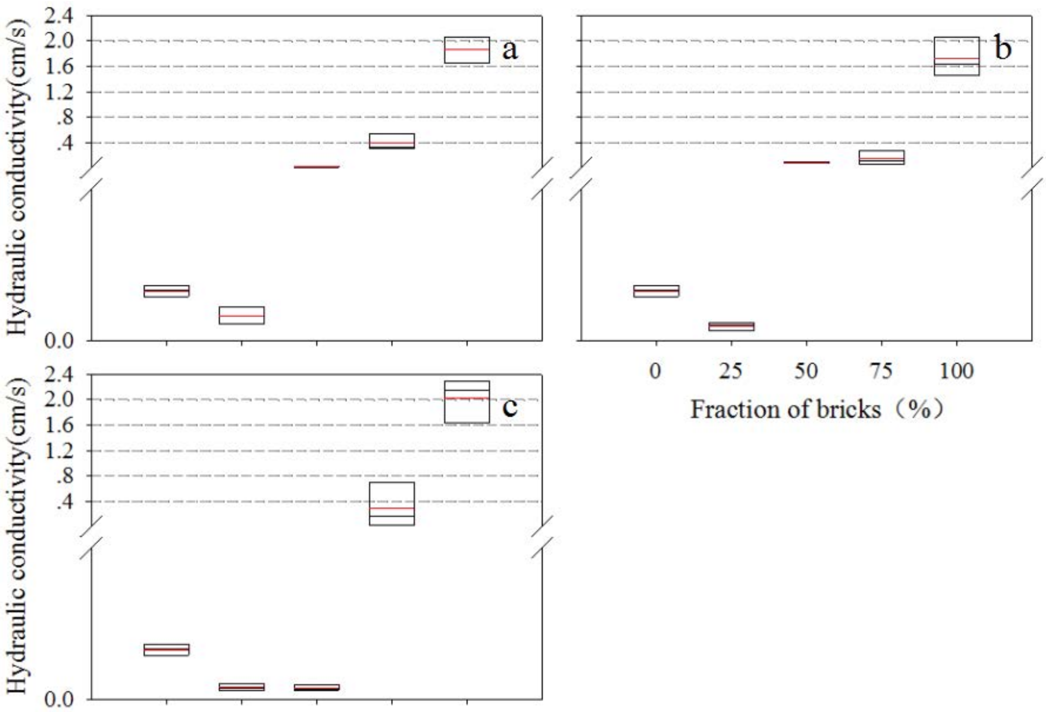


Fig. 6. Hydraulic conductivity of waste bricks with a size of 1–3 mm: (a) red bricks (b) concrete blocks, and (c) burn-free bricks.

mixing together soil and red bricks with a particle size of less than 1 mm. Belindae believes that the change in hydraulic conductivity is due to a compaction of the filter media [33]. Different from using only red bricks filters, adding soil will incur a compaction process, which may destroy the water pathway, reducing the capacity to convey water through the filters. Different from a small particle size, the hydraulic conductivity of red bricks with lager particles is greater than the soil filter medium alone, except 25% red bricks. This may be due to the inherent high porosity of the filter media [33]. Further research should focus on whether the filter media can provide lifetime service.

A comparison of concrete blocks of different particle sizes is shown in Figs. 5b and 6b. Fig. 5b indicates the hydraulic conductivity of concrete blocks with a size of less than 1 mm, where the mean hydraulic conductivity at different percentages are $1.53 \times 10^{-3}$, $3.73 \times 10^{-3}$, $4.96 \times 10^{-3}$, and $1.25 \times 10^{-2}$ cm/s, which is mostly larger than the hydraulic conductivity of the soil filter media. This may be related to the structure of the concrete blocks. Concrete blocks have an inherently high porosity, and their microstructure shows that they have the most spherical rough. This material fits with soil filter media after adding soil, and the water pathway will not be clogged. Fig. 6b shows the hydraulic conductivity of concrete blocks whose particle size ranges from 1 to 3 mm, and whose mean hydraulic conductivity at different percentages is $1.07 \times 10^{-3}$, $8.85 \times 10^{-2}$, 0.153 cm/s, and 1.72 cm/s. As the particle size increases, the gap between the particles will increase. This explains the change in hydraulic conductivity. When limited to a low proportion of concrete bricks, the filter media become rammed. It is thus necessary to determine the correct ratio when used in a bio-filter.

The mean of the hydraulic conductivity of burn-free bricks with different sizes is shown in in Figs. 5c and 6c. The hydraulic conductivity of burn-free bricks with a particle size of less than 1 mm is $7.07 \times 10^{-4}$, $8.79 \times 10^{-4}$, $2.72 \times 10^{-3}$, and $1.14 \times 10^{-2}$ cm/s. In addition, at a particle size of 1–3 mm, the conductivity is $8.87 \times 10^{-4}$, $8.35 \times 10^{-4}$, 0.297, and 2.02 cm/s. This is due to the lowest structural strength of the burn-free bricks. When mixed with soil media, the water pathway will be damaged by the media. As the pressure increases, the unstable structure of burn-free bricks leads to small particles, leading to the destruction of the original water pathway in the soil filter media. Tadele [8] also believe that hydraulic loading can lead to a decrease in hydraulic conductivity because of the compaction of the filter media. It has been reported that the destruction of the gap structure can lead to a decrease in hydraulic conductivity [34]. As the analyses in Figs. 5 and 6 indicate, the lowest hydraulic conductivity has usually been found in 25% bricks. The hydraulic conductivity will increase as the ratio of waste bricks increases; concrete blocks have their optimum hydraulic conductivity at the same particle size in the three types of waste bricks.

In consideration of the use of bio-retention, a material with a particle size ranging from 1 to 3 mm should be paved onto the upper layer. This is because a material with this particle size has better permeability than materials with a 1 mm particle size can effectively prevent clogging, extend the service period, and reduce the labor of paving the drainage layer. From the point of view of hydraulic conductivity, concrete blocks are a suitable material for application in a bio-retention system.

### *3.3. Phosphate adsorption capacity of bricks*

In this study, the result of the adsorption rate of the three types of waste bricks with different particle sizes at different concentrations of phosphate are shown in Fig. 7. The phosphorus adsorption rate of red bricks is the lowest of the three types of bricks considered, the most possible reason for which is that the surface of the red bricks is relatively smooth. The trend in phosphorus adsorption rate by the three materials is as follows: When the concentration of phosphorus approaches 3 mg/L, the adsorption rate of phosphorus is significantly decreased. When the phosphorus concentration is 3 mg/L, the adsorption rate of phosphorus by red bricks is less than 10%, whereas that of the cement blocks and non-burned bricks is less than 40%. Among them, the burn-free bricks show the best adsorption capacity for phosphorus, and their particle size is independent of the phosphorus adsorption.

In addition, the adsorption capacities of the different materials were tested, the results of which are shown in Fig. 8. The phosphate adsorption capacity of red bricks is displayed in Fig. 8a, and the adsorption capacity was shown to increase along with the increase in particle sizes. The adsorption capacity is related to the characteristics of the material. The maximum specific surface area was shown to be in accord with the particle size, ranging from 3 to 5 mm, as shown in Fig. 4a. The concentration of the phosphorus solution has few effects on the adsorption capacity.

The adsorption capacity of concrete blocks is shown in Fig. 8b, which indicates that concrete blocks with a particle size of less than 1 mm have the maximum phosphate adsorption capacity at the same solution concentration. The adsorption performance of each particle size is similar in the case of a low concentration (less than 3 mg/L), which is similar to that of burn-free bricks, as shown in Fig. 8c. It has been reported that the range of phosphorus concentration was from 0.5 to 1.5 mg/L in urban rainwater-runoff [35]. Burn-free bricks have the highest adsorption capacity, as indicated in Fig. 8c. However, its hydraulic conductivity has shown that the material is ill suited for application in a biofilter.

In fact, the material has a characteristic inertness, using physical or chemical method is a way to change its properties to improve its adsorption capacity.

## 4. Applications and analysis

The rapid urbanization process in China has led to highly complex urban environmental problems such as urban flooding, water pollution, and a heat-island effect [36]. To promote a sustainable urbanization strategy, the Chinese government announced its "sponge city" initiative at the end of 2013 to build urban infrastructure. Unlike a traditional "fast drainage" approach, the new paradigm calls for natural processes such as the use of soil and vegetation as part of an urban runoff control strategy [37]. The cores of these measures are infiltration and detainment.

Construction waste containing a larger number of waste bricks has been produced through the process of urbanization.

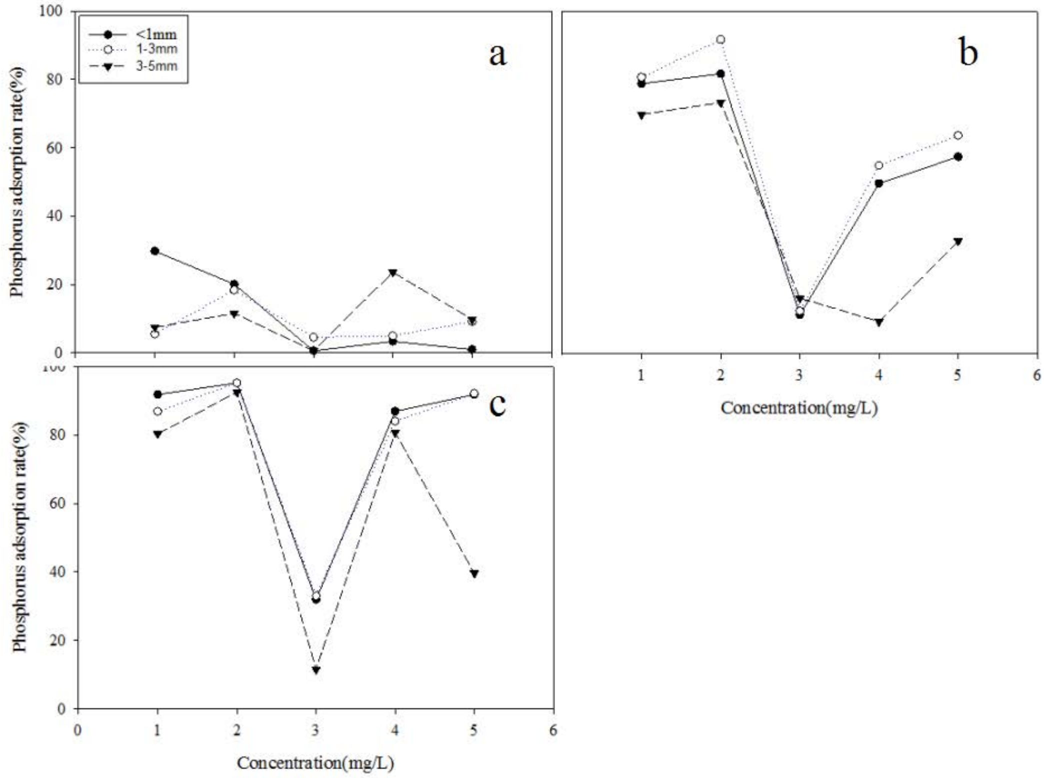


Fig. 7. Phosphate adsorption rate of samples at different concentrations: (a) red bricks, (b) concrete blocks, and (c) burn-free bricks.

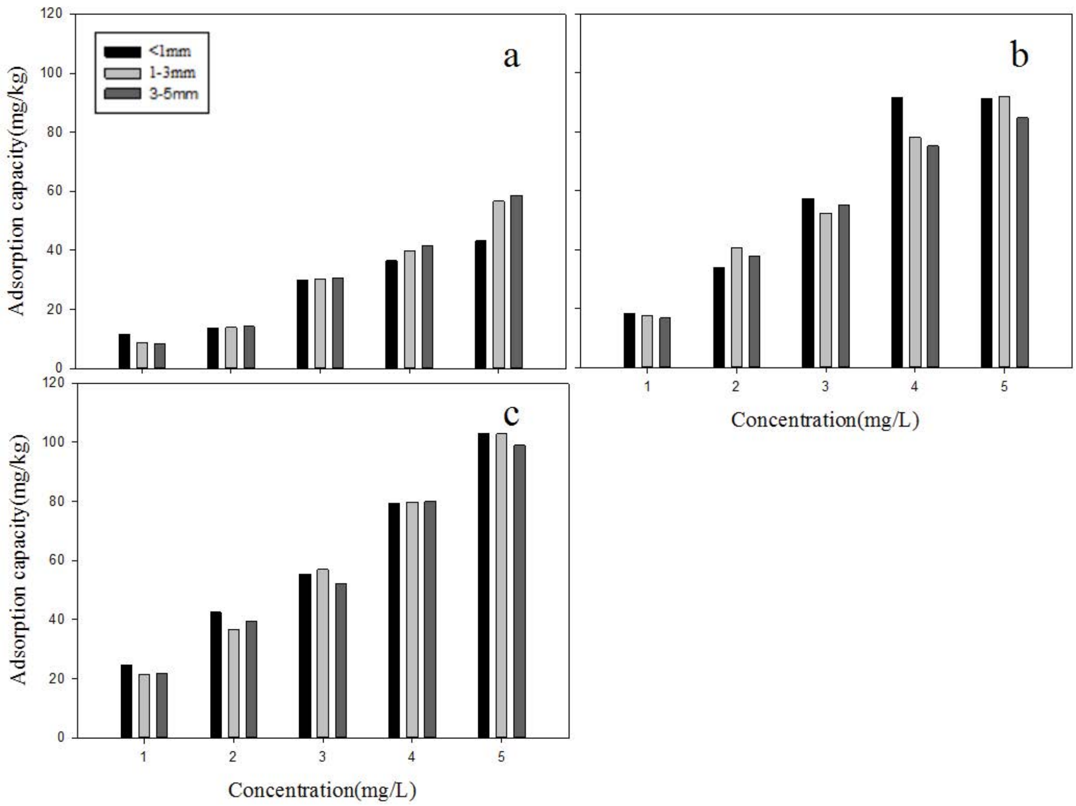


Fig. 8. Phosphate adsorption capacity of samples at different concentrations: (a) red bricks, (b) concrete blocks, and (c) burn-free bricks.

Waste bricks in China are generally reproduced into new bricks at present. We assumed that waste bricks would be applied in a bio-filter directly without a reworking process.

In this study, the hydraulic conductivity and adsorption capacity of waste bricks were researched. The results indicate that common waste bricks have a good adsorption capacity and hydraulic conductivity. Thus, they are suitable for application in a bio-filter. A diagram of the recycling process is shown in Fig. 9.

The common bio-filter from top to bottom has a retained water layer, a planting layer, a packing layer, and a drainage layer. The depth ratio of the different layers is normally set as 0.1:0.15:0.6:0.15 [38]. In consideration of the growth of plants, a certain amount of space should be reserved. Thus, the model with 25% waste bricks with particle sizes ranging from 1 to 3 mm and 75% soil was suggested for application in the planting layer. The above study illustrates that a particles that sizes less than 1 cm holds significant permeability and absorptive capacity, and to achieve the best permeability, 50% waste bricks was selected. This type of waste brick meets the conditions of a large spread in the packing layer. The drainage layer requires an effective hydraulic conductivity, and larger sized particles of more than 5 cm can be employed.

The selection of concrete blocks was due to their high hydraulic conductivity and adsorption capacity among the three types of waste bricks considered. The quantity of demand of waste bricks estimated for use in a bio-filter at a particular city in China has been calculated, the results of which are shown in Table 2.

In its Leadership in Energy and Environmental Design, the USA has prescribed rainfall runoff to control 90% of its rainfall [39]. As the runoff control standard, 2.5% of annual rainfall is processed. Despite this low amount, the number of waste bricks required is significant, as shown in Table 3 (example for concrete blocks). The effective demand of waste bricks needs to omit the processing capacity of soil and plants. Considering the recycling of waste bricks, the actual use of abandoned bricks has a market value.

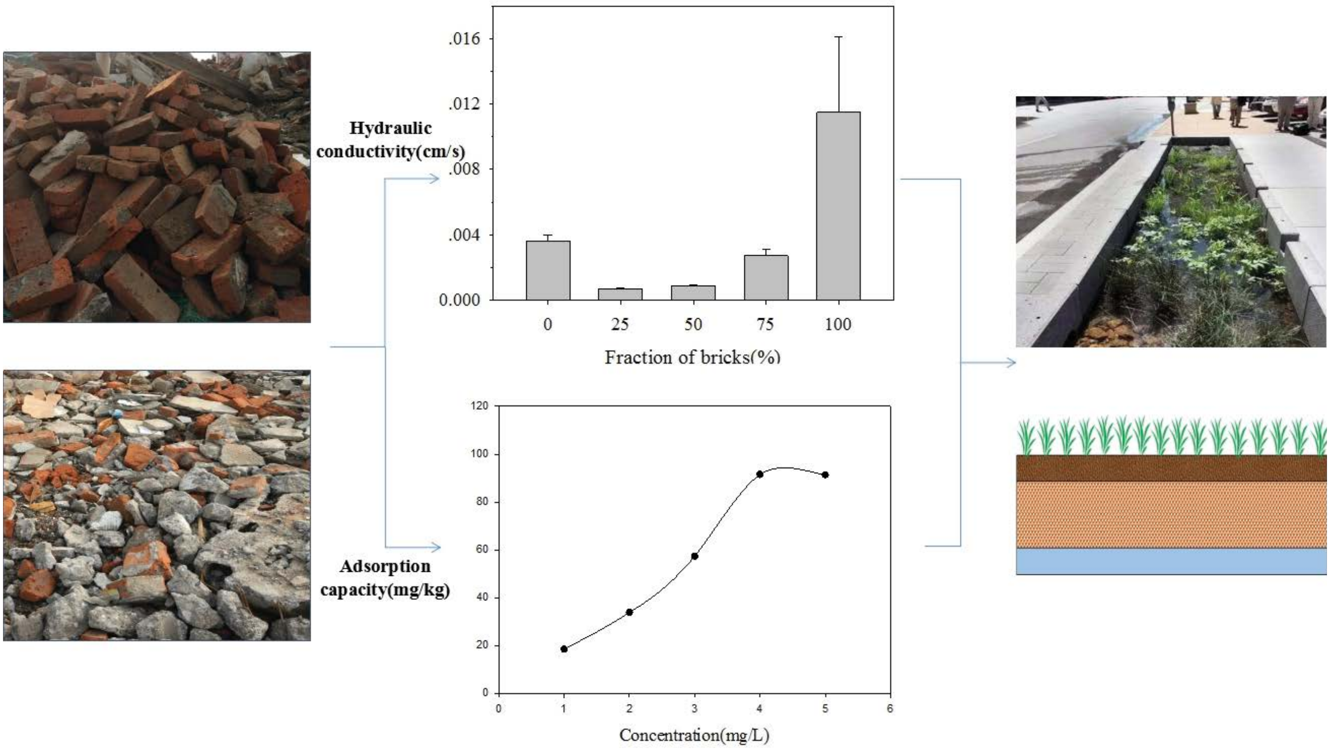


Fig. 9. Recycling of waste bricks.

Table 2
Estimated demand of concrete blocks based on area of paved city roads

| Serial number | City | Area of city paved roads (10,000 m$^2$) | Area of bio-retention (10,000 m$^2$) | Requirement of material (1,000 t) | | |
|---|---|---|---|---|---|---|
| | | | | <1 mm | 1–3 mm | 3–5 mm |
| 1 | Beijing | 14,316 | 715.8 | 30.24 | 3.85875 | 15.18 |
| 2 | Shanghai | 10,582 | 529.1 | 22.32 | 2.85 | 11.19 |
| 3 | Tianjin | 14,466 | 723.3 | 30.51 | 3.89625 | 15.285 |
| 4 | Chongqing | 17,776 | 888.8 | 35.5 | 4.78875 | 18.795 |

Table 3
Estimated demand of concrete blocks based on annual rainfall (mm)

| Serial number | City | Annual rainfall (mm) | Content of Phosphorus (mg/m²) | Requirement of material (t/m²) |
|---|---|---|---|---|
| 1 | Guangzhou | 2,939.7 | 2,234 | 0.1117 |
| 2 | Nanchang | 1,869.0 | 1,890.5 | 0.094525 |
| 3 | Haikou | 1,913.7 | 1,861.3 | 0.093065 |
| 4 | Fuzhou | 2,263.4 | 1,628.0 | 0.0814 |
| 5 | Guiyang | 1,045.8 | 1,562.0 | 0.0781 |
| 6 | Chongqing | 1,348.0 | 1,452.1 | 0.072605 |
| 7 | Changsha | 1,704.8 | 1,386.8 | 0.06934 |
| 8 | Hangzhou | 1,797.3 | 1,359.9 | 0.067995 |
| 9 | Shanghai | 1,596.1 | 1,295.3 | 0.064765 |
| 10 | Nanning | 1,546.4 | 1,234.7 | 0.061735 |
| 11 | Wuhan | 1,827.1 | 1,208.6 | 0.06043 |
| 12 | Hefei | 1,502.0 | 1,180.2 | 0.05901 |
| 13 | Nanjing | 1,807.7 | 1,091.1 | 0.054555 |
| 14 | Kunming | 1,150.2 | 1,078.3 | 0.053915 |
| 15 | Chengdu | 983.9 | 975.0 | 0.04875 |
| 16 | Xi'an | 456.0 | 658.7 | 0.032935 |
| 17 | Lasa | 551.6 | 637.8 | 0.03189 |
| 18 | Zhengzhou | 833.0 | 551.6 | 0.02758 |
| 19 | Jinan | 1,008.2 | 521.2 | 0.02606 |
| 20 | Beijing | 669.1 | 461.7 | 0.023085 |
| 21 | Xining | 444.1 | 446.8 | 0.02234 |
| 22 | Changchun | 890.8 | 446.0 | 0.0223 |
| 23 | Lanzhou | 310.0 | 435.9 | 0.021795 |
| 24 | Taiyuan | 429.1 | 429.1 | 0.021455 |
| 25 | Ha'erbing | 537.8 | 410.4 | 0.02052 |
| 26 | Huhehaote | 531.3 | 394.7 | 0.019735 |
| 27 | Shenyang | 968 | 363.9 | 0.018195 |
| 28 | Wulumuqi | 387.1 | 297.0 | 0.01485 |
| 29 | Shijiazhuang | 712.6 | 293.1 | 0.014655 |
| 30 | Yinchuan | 264.9 | 170.4 | 0.00852 |

## 5. Conclusions

In this study, we examined the hydraulic conductivity and adsorption capacity of different waste bricks in various forms. We reported that the filler material increases with an increase of the proportion of bricks applied. When compared with the same group, the best hydraulic conductivity appears in burn-free bricks. However, the small particle size will affect the hydraulic performance of the material, which is due to the destruction of the pore structure of the waste bricks. Through a study on the adsorption capacity, we reported that all waste bricks have a good adsorption capacity for phosphorus. As a conclusion, the adsorption capacities of the three materials are not the same; that of red bricks is proportional to the particle size, whereas that of concrete blocks and burn-free bricks decreases with the increase in particle size. The hydraulic conductivity and adsorption capacity of the three materials meet the conditions for use in a bio-filter. As inferred, the use of waste bricks in major cities is huge. In the future, the recycling of waste bricks to solve the problem of a large amount of packing required for bio-filters will bring about tremendous economic benefits to China.

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